HORIZONS User Manual
Version 3.12 (January 4, 2005)

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INTRODUCTION

PURPOSE:

The JPL Horizons On-Line Ephemeris System provides easy access to key solar system data and flexible production of highly accurate ephemerides for solar system objects. This includes 170,000+ asteroids & comets, 128 natural satellites, 9 planets, the Sun, select spacecraft, and several dynamical points such as Earth-Sun L1, L2 and system barycenters. Users may define their own objects, then use the system to integrate the trajectory, or conduct parameter searches of the comet/asteroid database, searching on combinations of up to 42 different parameters. Rise, transit and set may be identified to the nearest minute. Close-approaches by asteroids and comets to planetary bodies (and Ceres, Pallas, and Vesta) can be easily identified. Orbit uncertainties can be computed for asteroids and comets.

More than 100 different observational and physical aspect quantities can be requested at intervals for both topocentric and geocentric situations in one of 9 coordinate systems and 4 time scales (CT, TT, UT, Civil). Over 750 Earth station locations are on file, along with several on other major bodies. Users may search for or define topocentric site coordinates on any planet or natural satellite (with known rotational model), if the desired site is not predefined. Output is suitable for observers, mission planners and other researchers, although this determination is ultimately the users' responsibility.

Five types of customizable output can be requested:

1. Observables (RA/DEC, Az/El, physical aspect, angles, etc.)
2. Osculating elements
3. Cartesian state vectors
4. Close approaches to planets (and Ceres, Pallas, and Vesta)
5. SPK binaries (asteroids and comets only)

The first four are ASCII tables. Output is returned to the user via e-mail, FTP or Kermit protocols. Table output can be requested in a format suitable for spreadsheet import. SPK file output allows user programs to reproduce the integrated target state at any instant. The SPK files can be used by existing visualization, animation and mission-design software.

The underlying planet/satellite ephemerides and small-body osculating elements are the same ones used at JPL for radar astronomy, mission planning and spacecraft navigation.

OVERVIEW OF USAGE:

There are three different ways to access the program:

- Telnet (full access, active interactive prompt-based interface):
    1. Telnet directly to the system (telnet ssd.jpl.nasa.gov 6775). No account or password is required.
    2. Specify an object to get a summary data screen.
    3. Follow prompts. At any prompt, type ? or ?! for short and long explanations.
    4. Transmit results to your system by e-mail, FTP or Kermit

- E-mail (full access, except for SPK file production, batch interface):
    1. Send e-mail to "horizons@ssd.jpl.nasa.gov" with subject "BATCH-LONG".
    2. An example command file will be mailed back to you.
    3. Edit this text file, then mail it back with the subject header "JOB".
    4. Results of your request are mailed back to you.

- Web (partial access, passive interactive GUI interface):
    1. Point your browser to http://ssd.jpl.nasa.gov/horizons.cgi

The Horizons system was intended to be easy to use and should have a step-function learning curve. The remainder of this documentation summarizes system capabilities, but is not necessary for successful use.

While using the telnet system, type "?" or "?!" at any prompt for an explanation of options. See ACKNOWLEDGEMENTS section for contact information.

CONNECTING TO THE SYSTEM

TELNET:

The Horizons on-line ephemeris and data system is available as a telnet service. This is suitable for people who want full access to all program features in an interactive prompt-based way. From a telnet-capable machine, preferably running a "VT100" type terminal emulation, telnet to

"ssd.jpl.nasa.gov 6775",

... where 6775 is a port number. From within a web-browser, such as Netscape, enter location "telnet://ssd.jpl.nasa.gov:6775". The system will start a terminal session automatically. No user-ID or password is required.

If a user-name/password is requested, you did not specify the port number. A few PC-type telnet programs seem not to fully implement the telnet protocol and may not pass the port number to the network, or may need to be reconfigured to function properly or may have a different syntax for specifying port numbers. Consult your user's guide if you have a problem.

The system will also attempt to determine your window size. If it cannot, it will default to a 24 row by 79 column screen display. If this is inappropriate, and your display paging is choppy, manually set your screen size by using the command "TTY {rows} {columns}", where {rows} and {columns} are replaced by appropriate integers.

Window sizes less than 79 columns aren't recommended since data-screen displays are formatted with that minimum size in mind and will be difficult to read on something smaller.

WEB:

Point your browser to http://ssd.jpl.nasa.gov/horizons.cgi. This graphical interface is intended for the more casual user or general public and offers access to a subset of program features using pull-down menus, fill-in boxes and buttons to click.

E-MAIL:

The program can also be controlled by sending e-mail messages to the address "horizons@ssd.jpl.nasa.gov". Response is determined by the subject of the message. This option is for those who want access to most program features without the overhead of answering prompts or manipulating graphical interfaces; generally those already familiar with what the program does and who know what they want.

To get started, send e-mail to the above address with the subject "BATCH-LONG". The latest, fully-commented example run-stream will be mailed back. Edit this file to produce the results you want, then mail back with the subject "JOB". Acceptable e-mail subject commands are:

```
SUBJECT HEADER  MEANING
--------------  ------------------------------------------------------------
JOB             Horizons run-stream
DOC-TEXT        Request ASCII (plain-text) version of current documentation
DOC-PS          Request PostScript version of current documentation
BATCH-LONG      Request latest fully commented example batch file
BATCH-BRIEF     Request latest example batch file without comments
QUESTION        Message forwarded to cognizant engineer
```

GENERAL DEFINITIONS

The remainder of this document uses these abbreviations and terms. Understanding their meaning will help you properly interpret program documentation and output.

RA
Right ascension; the angular distance on the celestial sphere eastward along the celestial equator from the reference equinox to the meridian of the object. RA is analogous to longitude, with the plane containing the equinox defining zero RA much as the Greenwich meridian defines zero longitude. Expressed in units of hours, minutes and seconds or degrees, as requested.

DEC
Declination; the angular distance on the celestial sphere north (positive) or south (negative) of the celestial equator. It is analogous to latitude. Usually expressed in degrees.

AZ
Azimuth; the angle measured eastward along the "horizon" (the plane perpendicular to the local zenith) from the North to the point where the meridian passing through local zenith and the object intersects the horizon plane.

EL
Elevation; the angular distance above or below the plane perpendicular to the local zenith. Note this plane is not necessarily the visible horizon, due to station elevation ("horizon dip" effect).

Geometric coordinates
Referred to the mean equator and equinox of a particular reference frame (ICRF/J2000.0 or FK4/B1950.0). Geometric coordinates are the true, or instantaneous states of a body at a particular ephemeris time.

Astrometric coordinates
Accounts for the finite but varying amount of time it takes light to travel from the target to the observer and is expressed with respect to the mean equator and equinox of a particular reference frame (ICRF/J2000.0 or FK4/B1950.0).

Apparent coordinates
Takes into account factors which appear to change target position with respect to the background stars and inertial coordinate system: light-time, stellar aberration, the relativistic deflection of light. Usually, a final rotation to some "of-date" coordinate system is performed, such as precession-nutation to true-equator and equinox-of-date.

Refracted coordinates
Apparent coordinates approximately corrected for atmospheric refraction. Available only for Earth-based sites.

Small body
Refers to a comet or asteroid for which the trajectory is integrated from orbital elements. Typically no cartographic coordinate system is available, with the exceptions, so far, being Gaspra and Ida.

Major body
Refers to a planet, natural satellite, spacecraft or the Sun. In special cases, a comet or asteroid can be redefined as a major body. Only major bodies can be coordinate centers (observing sites). State vectors are interpolated from previously defined ephemerides, such as DE-405, which are stored as Chebyshev coefficients. Interpolation recovers the state the mm level.

Target body
Refers to the object of interest, selected by the user. It can be a major-body or small-body.

Primary body
Refers to closest body about which a target body orbits. For natural satellites, this would be a planet, although they orbit the Sun as well. For planets and small-bodies, the primary body is the Sun.

OBJECT SELECTION

Effective use of this system requires knowledge of how to select objects. The two classes of objects, accessed slightly differently, are the major bodies (planets and satellites) and small bodies (comets and asteroids). Accessing the different object types is described in the sections below.

MAJOR BODIES

Type 'MB' to get a list of all major-body strings that can be used to search on. To select a major body, enter one of the following:

1. A string to search on ("Mars" or "Trit")
2. A JPL ID integer code or fragment
3. An IAU code

Examples (at the main prompt):

```
Horizons> mars  (uniquely select Mars center; '499' does same)
Horizons> 501   (uniquely select Io)
Horizons> N*    (list all major bodies with 'n' in an ID field)
```

Major planets may have two integer ID's. Those >100, ending in 99 (such as 199, 299, 399, etc.) refer to planet CENTERS. To select planet SYSTEM BARYCENTERS, use the codes less than 10 (1, 2, 3). For example, "399" is the Earth's center, '3' is the Earth-Moon Barycenter and "301" is the center of the Moon. For Mercury, Venus and Mars, there is no significant difference between planet-center and system barycenter (1=199, 2=299, 4=499, etc).

If a planet name is entered, it may not be considered unique if a distinct system barycenter is present. For example, if "Saturn" is entered, a list containing "Saturn" and the "Saturn Barycenter" will be returned. To specify Saturn (the planet-center), you must use its unique ID code, "699".

System barycenters are available over longer time-spans than planet-centers.

SMALL BODIES

To select an asteroid or comet, enter a list of parameters to search on SEPARATED BY A SEMI-COLON (;). TYPE 'SB' FOR LIST OF 40 FIELD KEYWORDS THAT CAN BE MATCHED, or see list later in this document. Match symbols are from the set { >, <, <>, = }.

Examples (at the main prompt):

```
Horizons> A < 2.5; IN > 7.8; STYP = S; GM <> 0; (match parameters)
Horizons> Vesta;       (or "ASTNAM = Vesta;" for faster search)
Horizons> DES = 1993*; (Objects with designations containing 1993)
Horizons> 1;           (Object in file position #1)
Horizons> ;            (Enter your own elements)
```

For example, "A < 2.5; IN > 7.8; STYP = S, GM <> 0; " searches for all S-type small-bodies with semi-major axis less than 2.5 AU and inclination greater than 7.8 degrees with a known (non-zero) GM. Spaces in the command are not considered, nor are upper/lower-case distinctions.

Exceptions are object names and designations. Name searches consider spaces. Designation searches consider spaces AND upper/lower-case. If you want to match a fragment of a name or designation, end it with a '*' (e.g. DES = 1993*;). Otherwise, it is assumed a complete name or designation is specified and the search must match exactly and completely.

For example:

```
NAME = CERES;   (matches only if object name is "Ceres")
NAME = CERES*;  (match "Ceres", "Monoceres", etc)
```

The same keyword can be used more than once in a search command. For example, "IN >10; IN < 20;" will list those objects possessing an inclination between 10 and 20 degrees. If the directive "LIST;" is in the search request, the matched parameters will be displayed. For example, "IN > 150; LIST" will display the inclination of each object with inclination greater than 150 degrees.

Once a small-body is uniquely identified, a screen of data will be displayed. If more than one small-body matches given parameters, a list of matching objects is displayed. Individual objects from the matched list can then be requested by giving the displayed record number followed by a semi-colon.

The semi-colon is used to indicate a small-body request and resolve number ambiguities. For example, if you enter '1' you will select Mercury Barycenter. Enter '1;' to retrieve the small-body in record #1 (Ceres).

Small-body record numbers are assigned as follows:

```
Record # range    Object type
---------------  ------------------------------------------------------
     1 -> 100000  Reserved for NUMBERED asteroids (record # = asteroid #)
100001 -> 400000  Reserved for UNNUMBERED asteroids
400001 -> 500000  Reserved for COMET APPARITIONS
```

Elements for more than one comet apparition may be listed ("apparition" refers to a particular perihelion passage), since out-gassing near perihelion can alter the orbit for each passage. Select an apparition from the list with the closest epoch prior to the date of interest for the ephemeris.

The record (or file) number of unnumbered asteroids and comet apparitions should NOT be considered constants; they may change as the database is updated.

To enter your own heliocentric ecliptic elements, type ";". This capability is described in more detail in a later section.

COORDINATE CENTER (OBSERVING SITE) SELECTION

While osculating element tables may be generated with respect to a major body center only, vector and observer tables may produce output with respect to an arbitrary observing site, defined with respect to a major body center.

EARTH SITES

For the Earth, a list of 750+ sites is predefined. The list generally matches that of the Minor Planet Center, expanding on radar sites (which have negative ID numbers on this system) as necessary. Station "500" is the geocenter.

NON-EARTH SITES

For non-Earth major bodies, station 500 also represents the body center. For those major bodies with IAU rotational models, additional topocentric sites may be defined. Spacecraft landing sites are typically predefined on non-Earth bodies.

USING A PREDEFINED SITE

There are several equivalent ways of specifying a location. The most general form is ...

site @ body

... where "site" is a numeric code or name fragment to match, and "body" is a numeric major body code or name fragment to match. A list of such major body codes follows later in this document.

Here are four equivalent ways of searching for the same Earth location:

```
Code         Meaning
-----------  ------------------------------------------------------------
675@399      Site #675 on Earth (Palomar Mountain)
palomar@399         "
675@                "
Palomar             "           (observer table only)
```

If an observer table has been requested, the @ may be dropped; the Earth will be assumed if an integer like "675" or a name fragment like "Palom" is input. For a vector table, the DIFFERENT assumption is made that a coordinate center request lacking a "@" symbol is a major body. For example, '10' would mean the Caussols site for an observer table, but "Sun" for a vector table. '10@' or '10@399' would mean the Caussols site for both table types.

If your specification returns more than one possible match, the list of matched sites is returned. Refine your site request to be more specific, by using numeric codes for example, and try again.

While one can spell out the names of the bodies and sites, it is possible unique matches won't be returned. Thus, use the unique ID numbers when known. For example, "675@Earth" will first look for the body, find both the Earth & Earth-Moon barycenter, thus have to quit before finding specific Palomar site coordinates. "675@399" is unique and avoids this problem. Spaces & upper/lower case are ignored.

Here are examples for sites on bodies other than the Earth:

Code	Meaning
Viking@499	List all defined Viking lander sites on Mars
Viking 1@499	Select Viking 1 landing site on Mars
1 @301	Site #1 on the Moon
500 @ 501	Io body center
3 @ 499	Site #3 on Mars

The asterisk ('*') can be used to generate lists:

Code	Meaning
*@301	List all predefined sites on the Moon
*@Phobos	List all predefined sites on the Martian moon Phobos
*@399	List all predefined sites on Earth
*@	List all predefined sites on Earth (observer/vector table)
*	List all predefined sites on Earth (observer/vector table)
*	List all major bodies (element table only)

There are a several ways to request a body-centered site for a major body.

Code	Meaning
500@601	Mimas body center
geo@601	"
g@601	"
g@Mimas	"
500@Deimos	Deimos body center
geo	Earth Geocenter
g@399	Earth Geocenter

INPUT OF TOPOCENTRIC SITE COORDINATES

For sites with IAU rotation models, topocentric sites may be input by the user as follows:

Code	Meaning
c @ Europa	Request prompting for user location on satellite Europa
coord @ 502	(same)

The following satellites DO NOT have rotation models, thus do not support topocentric site definition. Only body-centered observers can be defined:

Jupiter:
Himalia (506), Elara (507), Pasiphae (508), Sinope (509),
Lysithea (510), Carme (511), Ananke (512), Leda (512)

Saturn:
Hyperion (607)

Uranus:
Caliban (716), Sycorax(717)

Neptune:
Nereid (802)

After coordinate input is requested, the site location may be entered as either geodetic or cylindrical coordinate triplets, separated by commas:

GEODETIC (generally this means map coordinates)
E-long - Geodetic east longitude (DEGREES)
lat - Geodetic latitude (DEGREES)
h - Altitude above reference ellipsoid (km)

CYLINDRICAL
E-long - Angle eastward from XZ plane (DEGREES)
DXY - Distance from Z axis (KM)
DZ - Height above XY equator plane (KM)

This system always uses planetographic/geodetic coordinates. This is typically the one used on maps, such as those by the USGS, unless the map says otherwise. In these coordinates, the rotational pole of the body that lies on the positive (north) side of the invariable plane of the solar system (the plane perpendicular to the solar system's angular momentum vector) is called the "north pole".

Northern latitudes are positive, southern are negative. The planetographic latitude takes into account body oblateness and, for a point on the surface, is the angle between the body equatorial plane and the normal to the reference surface at that point. For a point not on the reference surface, the geodetic latitude is the latitude of the point on the reference surface where the normal passes through the point at some altitude (h) above the reference surface.

Prograde (or direct) rotation of a body is rotation eastward, or counter- clockwise, as seen from the north pole. For such bodies, east longitude is measured negatively to the east (0 to -360 degrees) from the prime meridian. Retrograde rotation is rotation clockwise (westward) as seen from the north pole. East longitude is measured positively to the east (0 to 360 degrees) from the prime meridian.

Exceptions are the Earth, Moon and Sun where longitude has historically been measured both east and west of the prime meridian 0 to 180 degrees. Though these bodies are direct rotators, longitude is nonetheless measured positively to the east on this system, 0 to 360 degrees, due to historical precedence. If the positive west longitude of a site on these 3 bodies is given, it should be input here as positive east longitude, which would be (360 - West Longitude). If the negative east longitude is given instead, for these exceptions only, one can input the negative east longitude. It will be converted to a positive east longitude on output, however.

The following major bodies are either retrograde or exceptions and require site input with positive east longitude:

```
Retrograde (+ east longitude):
 ------------------------------
    Venus (299), Arial (701), Umbriel (702), Titania (703),
    Oberon (704), Miranda (705), Cordelia (706), Ophelia (707),
    Bianca (708), Cressida (709), Desdemona (710), Juliet (711),
    Portia (712), Rosalind (713), Belinda (714), Puck (715),
    Uranus (799), Pluto (999), Charon (901)

 Also + east longitude (prograde exceptions):
 -------------------------------------------
    Sun (10), Earth (399), Moon (301)
```

All others are prograde and must be input with negative longitude east of the adopted prime meridian. Since such sites are usually expressed in terms of positive west longitude on maps, negative east longitude would be ...

```
              ( West longitude - 360 )
```

INTERPRETING NON-EARTH OBSERVER TABLES

When placing a site on a body other than the Earth, some definitions become useful:

Interfering body:

The largest other body in the system. Such a body can visually complicate observations at the site due to its brightness or by covering up the target. On the Earth, the "interfering body" is the Moon. On Io, it would be Jupiter. On Mars, it would be Phobos (largest body, though unlikely to genuinely interfere). Mercury and Venus have no interfering bodies.

Observer tables provide some optional quantities that can be used to characterize the effect of the interfering body (or IB): how far is the target from the IB in the plane-of-sky, is it obscured by the IB, what fraction of the IB is lit by the Sun as seen from the observing site, and so on.

Deflecting body:

This is the Sun PLUS the most massive object in the planet/satellite system (e.g. the system barycenter). These two masses are used to compute the relativistic deflection of light that can change the apparent position of the target body.

Other changes:

REFRACTION

There are no refraction effects modeled for non-Earth sites. Any request for refraction is ignored and the refraction angle will be zero. This affects rise-set determination on non-Earth bodies as well.

AIRMASS

There is no airmass model or airmass cut-off available for non-Earth sites. Any request for airmass computation is ignored.

APPARENT RA & DEC

The origin of Right Ascension for apparent coordinates on NON-EARTH sites with rotational models is the meridian containing the Earth equinox of

J2000.0. Apparent declination is with respect to the particular body's true equator-of-date. This allows an observer to align axes with the pole and use the local apparent sidereal time output by this system to set the RA origin and acquire the target.

For objects lacking a pole & prime meridian rotational model (spacecraft and certain asteroids that may have been redefined as "major bodies"), the reference frame (ICRF/J2000.0 or FK4/B1950.0) coordinate system is used to compute apparent places. That is, apparent RA and DEC are defined with respect to the Earth mean-equator and equinox of the frame epoch.

TIME

The print-time output by this system for observer tables (UT or TT) is the instantaneous time on Earth. For non-Earth sites, it is unrelated to the rotation of the body. Local apparent solar time at the observing site can be requested, as can the instantaneous light time from Earth to the non-Earth site.

LIMITATIONS OF NON-EARTH/MOON ROTATION MODELS

For bodies outside the Earth-Moon system, precession and nutation effects are usually not known to high accuracy. Thus, the NON-Earth/Moon IAU rotation models, used by this system to determine topocentric site motion relative to the inertial frame as a function of time, are good to about 0.1 degree in the present era.

For the gas giants Jupiter, Saturn, Uranus and Neptune, IAU longitude is based on the "Set III" prime meridian rotation angle of the magnetic field. By contrast, pole direction (thus latitude) is relative to the body dynamical equator. There can be an offset between the magnetic pole and the dynamical pole of rotation.

For many satellites and the planet Mercury, the official IAU pole direction was simply assumed perpendicular to the body's mean orbit plane, lacking better information. For many satellites in the IAU model, the rotation rate was assumed equal to the mean orbital period.

Some small satellite rotational models are strictly valid only at the time of the Voyager spacecraft flyby; extrapolation to other times is hazardous. Topocentric results for such bodies (610-614, for example) should be used cautiously if at all. Results in these cases reflect only the best available model, which is a suspect one.

As rotation models are refined through observation of surface features by visiting spacecraft (Cassini, etc.), Horizons will be updated to use the best officially sanctioned models available.

OTHER COMMANDS

```
 Program information:
    MB ............. Show planet/natural-satellite (major-body) ID fields.
    SB ............. Show small-body search-field names & meanings.
    NEWS ........... Display program news (new capabilities, updates, etc.).
    ?! ............. Extended help ('?' for brief help).

  Program controls:
    LIST ........... Toggle display of small-body match-parameter values.
    PAGE ........... Toggle screen paging (scrolling) on or off.
    EMAIL {X} ...... Set your email address to {X} for output delivery.
    TTY {R} {C}..... Check or reset screen size; "tty" or "tty 24 79" to set.
    X .............. Exit JPL on-line system (also "QUIT" or "EXIT").
    - .............. Return to the previous prompt (back-up!).


Short-cuts:

        * Move backward through the prompts by typing "-".
        * Quit from ANY prompt by entering 'q'.
        * To use a default (or previously entered value), press return.
        * After selecting an object, enter "e+" to produce an ephemeris
          format like the last one, without additional prompting.
```

SAVING PROGRAM SETTINGS

Telnet (interactive) users may go through program options once, then save all settings for recall during future sessions. This can save time, if you find yourself always changing certain defaults or routinely defining the same output format each time you connect. Others in

your organization may load and use the same pre-defined format settings by name.

To save program settings, go through the prompts and define the settings as you require. Then return to the main "Horizons>" prompt.

#1) Type "SAVE {NAME}", where {NAME} contains 1-12 characters.
#2) Next time you telnet to Horizons, type "LOAD {NAME}".

Your output preferences will then be loaded in as the new defaults.

If you make a mistake or want to change a setting later, two commands are relevant: DELETE and SAVE

DELETE a macro with command "DELETE {NAME}". Alternatively, change specific settings manually, then replace the stored macro with a SAVE to an existing name. Delete and replace operations require input of a confirming password. LOAD does not. Thus, anyone can use your settings if they know the macro name. Only those who know the password can change or delete a macro.

Start/stop dates are also saved in the macro, as is observing location. You need only load the macro and select the target. Remaining defaults will be as defined in the format macro. If the macro is for an individual (personal use), you may want to set the e-mail address prior to saving. Otherwise don't, so users of the macro will be prompted for it in the future.

A macro may be loaded, then specific settings overruled by responding to the program prompts. For example, if your last table prior to saving the macro was a "vector" table, that table type will be saved as the default.

Settings for the other table types are saved as well so, to access them, manually respond to the prompt requesting table type, over-riding the macro's "vector" default on that issue. Start and stop times are also macro settings that may commonly be overruled as necessary.

Ideally, macro names would be something clean and logical:

```
"OBS670-1" for macro #1 for Observatory Code 670, etc.
```

... but the name is up to you.

The use of macros may make it less likely to stumble upon new capabilities as they are added, though they will described here and in the system news, as appropriate.

INTEGRATOR DISPLAY

Comet and asteroid ephemerides are integrated from initial conditions called "osculating elements". These describe the 3-dimensional position and velocity of the body at a specific time. The integrator starts with this state and takes small time steps, summing the perturbing forces at each step before taking another step. A variable order, variable step-size integrator is used to control error growth. In this way, the gravitational attraction of other major solar system bodies on the target body trajectory is taken into account.

The integrator starts at the epoch, or time, of the osculating elements. It then integrates forward or backward, as necessary, to the start of the requested table. Once it reaches the table start time, it may have to reverse direction and go forward in time to generate the table.

Every 50th step will be displayed so the user can get some sense of the progress of the ephemeris. Direction reversals are also displayed. If output is requested at small time intervals, the integrator may proceed rapidly to the start of the table. There may then be long (apparent) pauses, as numerous interpolations within a given integration step are performed to compute states at closely spaced print times.

The last number on the integrator display line is the most recent step size in days.

SPECIFICATION OF TIME

ACCEPTED FORMATS:

Time may be specified many ways in addition to the primary form "YYYY-MMM-DD HH:MM". Of particular note are Julian day number and day-of-year forms. Examples are shown below. Input start times may be specified to 1/1000th of a second if the default output setting is changed from "minutes".

Generally, if the input start time has more digits of precision specified than the selected output format, start time will be truncated to the appropriate level. For example, if a start time of 23:45:12.4 is specified, but the output format is only set to minutes, start time will

automatically be changed to 23:45(:00.000).

```
               YOUR INPUT             PROGRAM INTERPRETATION
                  ------------------------  ---------------------
Recommended:      1997-May-5 12:30:23.3348   ( 5 MAY 1997 12:30:23.334 )

Acceptable:       1/9/96 3 12 59.2           ( 9 JAN 1996 03:13 )
                  1 9 96 3,12,59.2           ( 9 JAN 1996 03:13 )
                  2 jan 91 3:00 12.2         ( 2 JAN 1991 03:00 )
                  91 MAR 10 12:00:00         (10 MAR 1991 12:00 )
                  29 February 1975 3:00      ( 1 MAR 1975 03:00 )
                  10 October 29 3:58         (29 OCT 2010 03:58 )
                  dec 31 86 12               (31 DEC 1986 12:00 )
                  86-365 // 12               (31 DEC 1986 12:00 )
                  JUL 98                     ( 1 JUL 1998 00:00 )
                  JD 2451545.                ( 1 JAN 2000 12:00 )
                  JD2451545.                 ( 1 JAN 2000 12:00 )
                  278bc-jan-12 12:34         (B.C. 12 JAN  278 12:34)
                  AD 99-Aug-12 12:34         (A.D. 12 JAN   99 12:34)
                  bc 278-Jan-12 12:34        (B.C. 12 JAN  278 12:34)
```

The program will interpret other forms as well, but if you get too casual, you may end up with a surprise interpretation.

The program's time-span prompts indicate the earliest & latest dates that may be used for the selected target/center combination, as well as the type of time assumed being input (UT, CT, or TT).

For cartesian coordinates or osculating elements tables, only CT may be used. For "observer tables", output may be either UT or TT. TO CHANGE THE UT DEFAULT for observer tables, append a "TT" when entering START time. To switch back, append a "UT" to the start time.

The three time systems are described as follows:

CT
("Coordinate Time"); typically for cartesian and osculating element tables. The uniform time scale and independent variable of the ephemerides.

TT
("Terrestrial (Dynamic) Time"), called TDT prior to 1991, used for observer quantity tables. This is proper time as measured by an Earth-bound observer and is directly related to atomic time, TAI. TT periodically differs from CT by, at most, 0.002 seconds.

UT
is Universal Time This can mean one of two non-uniform time-scales based on the rotation of the Earth. For this program, prior to 1962, UT means UT1. After 1962, UT means UTC or "Coordinated Universal Time". Future UTC leap-seconds are not known yet, so the closest known leap-second correction is used over future time-spans.

TIME ZONE CORRECTIONS:

Output time-tags may also be in local civil time. When specifying start time, enter your time-zone correction in the format:

```
             YYYY-Mon-Dy HH:MM UT{s}HH{:MM}
```

... where

```
   {s} ...  optional sign (+ or -). If unspecified, it is assumed "+".
    HH  ...  integer hours time-zone difference from UT
  {:MM} ...  optional minutes offset (usually 0)
```

North American standard time (winter) zone corrections are as follows:

```
          Atlantic Standard Time (AST) =  UT-4 hours
          Eastern Standard Time  (EST) =  UT-5 hours
          Central Standard Time  (CST) =  UT-6 hours
          Mountain Standard Time (MST) =  UT-7 hours
          Pacific Standard Time  (PST) =  UT-8 hours
```

If daylight savings is in effect (summer), add one hour to above offsets.

For example, "1999-jun-2 12:30 UT-8" produces a table in Pacific Standard Time. A "-7" would provide Pacific Daylight Time (or MST, if it is winter).

GREGORIAN AND JULIAN CALENDAR DATES:

Input calendar dates 1582-Oct-15 and after are taken to be expressed in the extended Gregorian calendar system. Prior dates are assumed to be in the Julian proleptic calendar.

Historically, not all regions switched calendars at the same time (or even in the same century). Thus, the user must be aware of which calendar was in effect for a particular historical record. It should NOT be assumed this system's calendar automatically correlates with a date from an arbitrary historical document.

Here is the progression near the calendar switch point:

```
Calendar Type    Calendar Date   Julian Day Number
   -------------    -------------   -----------------
    Julian           1582-Oct-03        2299158.5
    Julian           1582-Oct-04        2299159.5 --->
     (skipped)      "1582-Oct-05"       2299160.5    |
     (skipped)      "1582-Oct-06"       2299151.5    |
     (skipped)      "1582-Oct-07"       2299152.5    |
     (skipped)      "1582-Oct-08"       2299153.5    |
     (skipped)      "1582-Oct-09"       2299154.5    |
     (skipped)      "1582-Oct-10"       2299155.5    |
     (skipped)      "1582-Oct-11"       2299156.5    |
     (skipped)      "1582-Oct-12"       2299157.5    |
     (skipped)      "1582-Oct-13"       2299158.5    |
     (skipped)      "1582-Oct-14"       2299159.5    |
    Gregorian        1582-Oct-15        2299160.5 <---
    Gregorian        1582-Oct-16        2299161.5
    Gregorian        1582-Oct-17        2299162.5
```

Note that Julian (calendar) dates are different than (and unrelated to) Julian day numbers.

Examination of this table shows that the date labels from Oct 5, 1582 through Oct 14, 1582 don't exist. Of course, the days themselves do, as is shown in the continuous Julian day number column; it's just a matter of what one calls them. If you specify a non-existent calendar date label that was "skipped", this program will automatically use a day number, as shown above, that maps into the previous Julian calendar system. For example, requesting a date of 1582-Oct-14 (skipped) is the same as requesting the Julian calendar date 1582-Oct-04.

ANCIENT DATES:

Objects 0-10, 199, 299, 301, 399 and 499 (planet barycenters, their equivalents and the Sun & Moon) are available over a 3000 B.C. to A.D. 3000 interval. When specifying ancient calendar dates, this system requires input in the "BC/AD" scheme. If no "BC" marker is input with a calendar date, it is assumed to be "AD". Exceptions are AD years less than 100 which must have an AD symbol in the date in order to be recognized as a valid year. For example, "66ad-jan-27" will be accepted, but "66-Jan-27" cannot be parsed.

In this system, there are no negative years. The progression is as follows:

```
  Julian Day Number       Labeling-convention
         (Jan 1 00:00)       BC/AD      Arithmetical
       -----------------     -----      ------------
           1720327.5          3bc            -2
           1720692.5          2bc            -1
           1721057.5          1bc             0
           1721423.5          1ad             1
           1721788.5          2ad             2
```

From this, one can see that no days (in the arithmetical year "0", for example) are skipped in the BC/AD scheme, but they do have a different label than in the corresponding arithmetical system.

Output observer-table lines begin with a 'b' in column 1, to indicate B.C. dates, and a space (" ") to indicate A.D. dates.

OUTPUT STEPPING:

Fixed time steps:

Output time steps are specified as integers with some associated units from the set {days, hours, minutes}. Example responses to the prompt include "30 days", "1 day", "10 min", and so on. To get half day steps, specify "12 hour".

It is possible to obtain output at less than 1 minute intervals (telnet & e-mail interfaces only). After specifying a start and stop time, give a positive integer as the "time-step", without giving units, such as "10". This will divide the time span into 10 parts. For example, if start and stop times are one hour (3600 seconds) apart, specifying a step of "240" will produce output every 15 seconds 3600/15 = 240 intervals). "3600" will produce output every second.

Rise/set and satellite eclipse circumstances may not be accurate to less than a minute since factors such as the primary's oblateness

and atmosphere are not currently modelled.

Time-varying steps:

Output is typically at fixed time intervals. However, observer tables may additionally be requested at time-varying steps based on an angular shift specification. That is, "output only if the object has moved at least X arcseconds in the plane-of-sky".

When specifying step-size, with the telnet or e-mail interfaces, respond with something like "VAR ####", where '####' is an integer from 60 to 3600 arcseconds. This will trigger output whenever the object's position is predicted to be '####' arcseconds different from the current output step in the observer's plane-of-sky.

To preserve system performance, the time-varying output mode uses a simple linear extrapolation to predict the time when the object should have moved the requested distance. Due to non-linearities in the object's actual motion in the plane-of-sky, this projection can be off by .1 to 5 (or more) arcsecs. Thus the angular-motion print criteria you give should be considered approximate.

Computed quantities will be exact for the given time in the output, but the particular output time may not be exactly that required for the requested angular change.

REFERENCE FRAMES

It is necessary to adopt a commonly agreed-upon coordinate system for describing the position and velocity of an object in three-dimensional space. This program has two basic frames available; the default is ICRF/J2000.0 which can be changed to FK4/B1950.0, if desired, at the appropriate prompt.

"J2000" selects an Earth Mean-Equator and dynamical Equinox of Epoch J2000.0 inertial reference system, where the Epoch of J2000.0 is the Julian date 2451545.0. "Mean" indicates nutation effects are ignored in the frame definition. The system is aligned with the IAU-sponsored J2000 frame of the Radio Source Catalog of the International Earth Rotational Service (ICRF). The ICRF is thought to differ from FK5 by at most 0.01 arcsec.

J2000.0 reference vectors have the following properties:

- +Z is normal to ICRF Mean Earth Equator of Epoch J2000.0
- +X is parallel to ICRF Mean Earth Dynamical Equinox of Epoch J2000.0
- +Y completes the right-handed system

"B1950" selects an inertial reference frame based on Earth Mean-Equator and FK4 catalog Equinox of Epoch B1950.0 (FK4/B1950.0), where the Epoch of B1950.0 is the Julian date at the start of the Besselian year B1950.0 (2433282.42345905). The Fricke equinox correction at Epoch is applied.

COORDINATE SYSTEMS

CARTESIAN VECTORS and OSCULATING ELEMENTS may be requested in one of three available coordinates systems derived from the selected basic reference frame. These systems are defined with respect to the reference frames (above) as follows:

Earth mean equator and equinox of reference epoch

```
 Reference epoch: J2000.0 or B1950.0
   xy-plane: plane of the Earth's mean equator at the reference epoch
   x-axis  : out along ascending node of the instantaneous plane of the
             Earth's orbit and the Earth's mean equator at the reference epoch
   z-axis  : along the Earth mean north pole at the reference epoch
```

Ecliptic and mean equinox of reference epoch

```
  Reference epoch: J2000.0 or B1950.0
   xy-plane: plane of the Earth's orbit at the reference epoch
   x-axis  : out along ascending node of instantaneous plane of the Earth's
             orbit and the Earth's mean equator at the reference epoch
   z-axis  : perpendicular to the xy-plane in the directional (+ or -) sense
             of Earth's north pole at the reference epoch.
```

Body mean equator and node of date

```
  Reference epoch: "of date"
   Reference plane: ICRF/J2000.0 or FK4/B1950.0
   xy-plane: central-body mean equator plane at reference epoch
```

```
    x-axis  : out along the ascending node of the central-body mean equator
              plane on the reference plane at the reference epoch
    z-axis  : along the central-body mean north pole at the reference epoch
```

OBSERVER TABLE COORDINATES, such as RA and DEC, may be with respect to two possible coordinate systems:

Earth mean equator and equinox of reference epoch (astrometric coordinates):

```
    Reference epoch: J2000.0 or B1950.0
    xy-plane: plane of the Earth's mean equator at the reference epoch
    x-axis  : out along ascending node of the instantaneous plane of the
              Earth's orbit and the Earth's mean equator at the reference epoch
    z-axis  : along the Earth mean north pole at the reference epoch

Body true equator and Earth equinox of date (apparent coordinates)
    Reference epoch: "of date"
    xy-plane: plane of the body's true equator at the reference epoch
    x-axis  : out along ascending node of instantaneous plane of the Earth's
              orbit and the Earth's true equator plane at the reference epoch
    z-axis  : along the body's true north pole at the reference epoch
```

SEARCHING FOR SMALL-BODIES

Search for small-bodies with following keywords (Type R=real, I=integer, C=char). Use comparisons from the set { <, >, <>, = }. Separate each field with a semi-colon. Example search formulation:

A < 2.5; IN > 7.8; STYP = S; GM <> 0;

The first group of keywords are common to asteroids AND comets:

```
 Type     Keyword     Description
 ----     -------     -----------
  C       NAME ...... Asteroid OR comet name fragment
  C       DES ....... Object designation
  R       EPOCH ..... Julian Date of osculating elements
  R       CALEPO .... Calendar date of osc. elements; YYYYMMDD.ffff
  R       A ......... Semi-major axis (AU)
  R       EC ........ Eccentricity
  R       IN ........ Inclination of orbit plane (DEG) wrt ecliptic
  R       OM ........ Longitude of Ascending Node (DEG) wrt ecliptic/equinox
  R       W ......... Argument of Perihelion (DEG) wrt ecliptic/equinox
  R       TP ........ Perihelion Julian Date
  R       CALTP ..... Perihelion calendar date; YYYYMMDD.ffff
  R       MA ........ Mean anomaly (DEG)
  R       PER ....... Orbital period (YRS)
  R       RAD ....... Object radius (KM)
  R       GM ........ Object GM (KM^3/S^2), only a few are known
  R       QR ........ Perihelion distance (AU)
  R       ADIST ..... Aphelion distance (AU)
  R       ANGMOM .... Specific angular momentum (AU^2/DAY)
  R       N ......... Mean motion (DEG/DAY)
  R       DAN ....... Heliocentric dist. (AU) of ascending node
  R       DDN ....... Heliocentric dist. (AU) of descending node
  R       L ......... Ecliptic longitude of perihelion (DEG)
  R       B ......... Ecliptic latitude of perihelion (DEG)
  I       NOBS ...... Number of astrometric determinations in solution
```

The next parameters are ASTEROID SPECIFIC. If one or more is used, the search will conclude faster by examining asteroids only. For example, including something like 'H > -10;' will limit the search to asteroids only:

```
  C       ASTNAM .... Asteroid name fragment (designation if unnamed)
  R       B-V ....... B-V color (asteroid)
  R       H ......... Absolute magnitude parameter (asteroid)
  R       G ......... Magnitude slope parameter; can be < 0 (asteroid)
  R       ROTPER .... Rotational period, hrs (asteroid)
  R       ALBEDO .... Geometric albedo (asteroid)
  C       STYP ...... Spectral type, Tholen scheme (asteroid)
```

The next parameters are COMET SPECIFIC. If one or more is used, the search will conclude faster by examining comets only. For example, including something like "M1 > -10;" will limit the search to comets only:

```
  C       COMNAM .... Comet name fragment (designation if unnamed)
```

```
I       COMNUM .... Comet number
R       M1 ........ Total absolute magnitude (comet)
R       M2 ........ Nuclear absolute magnitude (comet)
R       K1 ........ Total magnitude scaling factor (comet)
R       K2 ........ Nuclear magnitude scaling factor (comet)
R       PHCOF ..... Phase coefficient for k2=5 (comet)
R       A1 ........ Radial non-grav accel (comet), 10^-8 AU/DAY^2
R       A2 ........ Transverse non-grav accel (comet), 10^-8 AU/DAY^2
R       A3 ........ Normal non-grav accel (comet), AU/d^2
R       DT ........ Non-grav lag/delay parameter (comet), days
```

Only 1 of the 4 keywords 'ASTNAM', 'COMNAM', 'NAME' or 'DES' can be specified on a given search.

Directives:

There are 3 directives that may be used to limit or control searches:

Directive	Description
COM	Limit search to comets only
AST	Limit search to asteroids only
LIST	Display parameter values for matched objects. (This may be set as a default for all subsequent searches by typing "LIST" at the main system prompt, "Horizons>".)

For example,

```
"A < 2.5; IN > 10; AST;"        match parameters against asteroids ONLY.
"A < 2.5; IN > 10; AST; LIST;"  match AND display values of the parameters.
```

Contents of Small-body Database:

Excluded from the database are single opposition asteroids with observational data arcs less than 30 days, unless they are NEO's, "PHA's" or radar targets (which ARE included). Everything else is in.

Except for "PHA's" and NEOs, which are usually included within a couple hours of announcement, there can be a delay of a few days to a couple weeks before newly discovered objects (that meet the filter criteria) are added. Users can input their own objects, as described in the next section. The database is updated hourly with new objects and orbit solutions.

USER-SPECIFIED SMALL-BODIES

It is possible to define an object not in the database by inputting its HELIOCENTRIC ECLIPTIC elements and some other parameters. Type ';' at the main prompt. It is also possible to display a DASTCOM3 object, then "cut-and-paste" elements back into the program, varying parameters (such as magnitude), as needed. Cut-and-paste is a function of your local terminal capability.

```
PRESS <return> ON A BLANK LINE WHEN DONE. Input format is:

          LABEL= VALUE LABEL= VALUE ...
          LABEL= VALUE ...
      .
      .
```

... where acceptable label strings are defined as follows:

```
     EPOCH ....  Julian ephemeris date (CT) of osculating elements
     EC .......  Eccentricity
     QR .......  Perihelion distance in (AU)
     TP .......  Perihelion Julian date
     OM .......  Longitude of ascending node (DEGREES) wrt ecliptic
     W ........  Argument of perihelion (DEGREES) wrt ecliptic
     IN .......  Inclination (DEGREES) wrt ecliptic
```

Instead of {TP, QR}, {MA, A} or {MA,N} may be specified (not both):

```
     MA .......  Mean anomaly (DEGREES)
     A ........  Semi-major axis (AU)
```

```
N ........  Mean motion (DEG/DAY)
```

Note that if you specify elements with MA, {TP, QR} will be computed from them. The program always uses TP and QR.

OPTIONAL INPUTS

```
RAD ......  Object radius (KM)
AMRAT ....  Area-to-mass ratio (m^2/kg). Total absorption is assumed,
             so scale value to account for reflectivity. For example,
             if 15% of light is reflected, specify a value for AMRAT
             in which the actual value is multiplied by 1.15.
```

For asteroids, additional OPTIONAL parameters can be given:

```
H ........  Absolute magnitude parameter (asteroid)
G ........  Magnitude slope parameter; can be < 0 (asteroid)
```

For comets, additional OPTIONAL parameters can be given:

```
M1 ........ Total absolute magnitude (comet)
M2 ........ Nuclear absolute magnitude (comet)
K1 ........ Total magnitude scaling factor (comet)
K2 ........ Nuclear magnitude scaling factor (comet)
PHCOF ..... Phase coefficient for k2=5 (comet)
A1 ........ Radial non-grav accel (comet), AU/DAY^2
A2 ........ Transverse non-grav accel (comet),  AU/DAY^2
A3 ........ Normal non-grav accel (comet), AU/d^2
DT ........ Non-grav lag/delay parameter (comet), days.
```

You may enter each value on a separate line or several on one line. If you make a mistake, re-entering the label on another line will override the previously specified value. To erase a value, enter something like "H=", where no value is given. To cancel all input, enter "-" as the first character on a line. To log-out, enter a "q" or "x" as first character on a line.

When done, after having pressed <return> on a blank line, you will be asked whether the reference frame of the elements is FK5/J2000.0 or FK4/B1950.0. You will also be asked the object name.

Example input:

```
EPOCH= 2450200.5
 EC= .8241907231263196 QR= .532013766859137 TP= 2450077.480966184235
 OM= 89.14262290335057 W = 326.0591239257098 IN= 4.247821264821585
 A1= -5.113711376907895D-10 A2= -6.288085687976327D-10
```

CUSTOMIZING REQUESTED EPHEMERIDES

Keys are embedded in output ephemerides to assist with automated reading of the output by user's own software. The keys are defined as follows:

$$SOE Start of ephemeris
$$EOE End of ephemeris

Ephemerides may be customized by changing output default flags. The '*' symbols below denote login defaults. All tables may be optionally output in a "comma-separated-value" format for import into spreadsheets.

1. Cartesian state vector table

Any object with respect to any major body.

```
   Reference frame:
*      J2000 (ICRF/J2000.0)
       B1950 (FK4/B1950.0)

   Coordinate system:
       Earth mean equator and equinox of frame Epoch (J2000.0 or B1950.0)
*      Ecliptic and mean equinox of frame Epoch (J2000.0 or B1950.0)
       Central body mean equator and node of date
```

```
   Aberration corrections:
 *      NONE  (geometric state vectors)
        LT    (light-time)
        LT+S  (light-time & stellar aberration)

   Units:
       KM and seconds
       KM and days
       AU and days

   Quantities Output:

    Format   Output
    ------   ------
         1   Position components {x,y,z} only
         2   State vector {x,y,z,vx,vy,vz}
 *       3   State vector + 1-way light-time + range + range-rate
         4   Position     + 1-way light-time + range + range-rate
         5   Velocity components {vx, vy, vz} only
         6   1-way light-time + range + range-rate
```

2. Osculating elements table

Any object with respect to any major-body

```
   Reference frame:
 *      J2000 (ICRF/J2000.0)
        B1950 (FK4/B1950.0  )

   Coordinate system:
       Earth mean equator and equinox of frame Epoch (J2000.0 or B1950.0)
 *     Ecliptic and mean equinox of frame Epoch (J2000.0 or B1950.0)
       Central body mean equator and node of date

   Units:
       KM and seconds
       KM and days
       AU and days

 *   Output quantities (fixed):
       JDCT     Epoch Julian Date, Coordinate Time
        EC      Eccentricity
        QR      Periapsis distance
        IN      Inclination w.r.t. xy-plane (degrees)
        OM      Longitude of Ascending Node (degrees)
        W       Argument of Perifocus (degrees)
        Tp      Periapsis time (user specifies absolute or relative date)
         N      Mean motion (degrees/DU)
        MA      Mean anomaly (degrees)
        TA      True anomaly (degrees)
         A      Semi-major axis
        AD      Apoapsis distance
        PER     Orbital Period
```

3. Observer table

Any object with respect to geocentric or topocentric observer

Default quantities. Always output:
Time
Solar-presence
Lunar-presence

Selectable quantities. Output in order requested. No initial default exists. You will be prompted at least once. A detailed definition of these values follows, with the '*' symbols marking those quantities affected by user selection of airless or refraction-corrected apparent quantities. Quantities preceded by a '>' are statistical uncertainties that can be computed for asteroids and comets if a covariance is available, either in the database or supplied by the user. Numbers could change if new quantities are added:

```
 1. Astrometric RA & DEC  15. Sun sub-long & sub-lat  29. Constellation ID
*2. Apparent RA & DEC     16. Sub Sun Pos. Ang & Dis  30. Delta-T (CT - UT)
 3.   Rates; RA & DEC     17. N. Pole Pos. Ang & Dis *31. Obs eclip. lon & lat
*4. Apparent AZ & EL      18. Helio eclip. lon & lat  32. North pole RA & DEC
 5.   Rates; AZ & EL      19. Helio range & rng rate  33. Galactic latitude
 6. Sat. X & Y, pos. ang  20. Obsrv range & rng rate  34. Local app. SOLAR time
 7. Local app. sid. time  21. One-Way Light-Time      35. Earth->Site lt-time
```

```
 8. Airmass              22. Speed wrt Sun & obsrvr >36. RA & DEC uncertainty
 9. Vis mag. & Surf Brt  23. Sun-Obsrvr-Target angl >37. POS error ellipse
10. Illuminated fraction 24. Sun-Target-Obsrvr angl >38. POS uncertainty (RSS)
11. Defect of illumin.   25. Targ-Obsrv-Moon/Illum% >39. Range & Rng-rate sig.
12. Sat. angle separ/vis 26. Obsr-Primary-Targ angl >40. Doppler/delay sigmas
13. Target angular diam. 27. Pos. Ang;radius & -vel
14. Obs sub-lng & sub-lat 28. Orbit plane angle

 ... or select a pre-defined format below:
 A = All quantities      B = Geocentric only        C = Small-body geocentric
 D = Small-body topo.    E = Spacecraft geocentric  F = Spacecraft topocentric

 The alphabetic assignments specifically mean:
 A = 1-40                      B = 1-3,6,9-33        C = 1-3,9-11,13,18-29,
                                                       33,36-40
 D = 1-5,8-10,11,13,18-29,     E = 1-3,8,10,18-25,29 F = 1-5,8,10,18-25,29
     33-34,36-40
```

... with the small-body cases primarily skipping cartographic dependent quantities. Note that Ida and Gaspra are exceptions, having IAU-defined mapping grids, so that C & D options won't provide all available data for such objects. In the list below, '*' indicates initial program default settings.

```
      Reference coordinate frame:
*       J2000 (ICRF/J2000.0)
        B1950 (FK4/B1950.0 )
        Body true-equator and Earth equinox of-date

       Time scale:
*       UT  (Universal Time)
        TT  (Terrestrial Time)

       Time zone correction (used for UT-based tables only)

       Time format
*       Calendar
        JD (Julian date)
        Both

       Time output precision (calendar format only)
*       MINUTES (HH:MM)
        SECONDS (HH:MM:SS)
        FRACSEC (HH:MM:SS.fff)

       Right-ascension format
*       Hours, minutes, seconds of arc (DEC degrees, minutes, seconds)
        Decimal degrees

       High-precision RA/DEC output
*       No  (~ 10^-2 arcsec; HH MM SS.ff DD MM SS.f)
        Yes (~ 10^-4 arcsec; HH MM SS.ffff DD MM SS.fff)

       Apparent coordinate corrections
*       Airless apparent
        Refracted apparent

       Minimum elevation (integer value)
*       -90 degrees

       Maximum airmass (real value)
*       38.0 (refracted elevation = -0 deg)

       Rise/Transit/Set print ONLY
*       No
        TVH -- True visual horizon. Includes dip and refraction (Earth only).
        GEO -- Geometric horizon. Includes refraction (Earth only).
        RAD -- Radar horizon. Geometric horizon, no refraction.

       Skip Daylight
*       No
        Yes
```

DEFINITION OF OBSERVER TABLE QUANTITIES

The menu of observer table output quantities was shown above. The format of the table is as follows. "Labels" refers to column headings at the start of the table:

TIME
One output line for each step. The line begins with a 'b' if the date is BC, a blank (" ") if AD. This is followed by the date and time, which is either UT or TT, in calendar or JD format (or both), depending on user defaults.

SOLAR PRESENCE
Time tag is followed by a blank, then a solar-presence symbol:

```
'*'  Daylight (refracted solar upper-limb on or above apparent horizon)
'C'  Civil twilight/dawn
'N'  Nautical twilight/dawn
'A'  Astronomical twilight/dawn
' '  Night OR geocentric ephemeris
```

INTERFERING BODYLUNAR PRESENCE
The solar presence symbol is immediately followed by another marker symbol:

```
'm'  Refracted upper-limb of Moon/IB on or above apparent horizon
' '  Refracted upper-limb of Moon/IB below apparent horizon OR
      geocentric ephemeris
'r'  Rise    (target body on or above cut-off RTS elevation)
't'  Transit (target body at or past local maximum RTS elevation)
's'  Set     (target body on or below cut-off RTS elevation)
```

The 'rts' codes will be displayed under two conditions only: if the print interval is less than or equal to 30 minutes or the RTS-only print option has been selected.

For non-Earth observing sites, no twilight/dawn codes (C, N, or A) are output, refraction is not modelled and the interfering body marker is 'x' instead of the 'm' reserved for Earth's Moon.

STATISTICAL UNCERTAINTIES

Output for asteroids and comets can include formal +/- 3-standard-deviation statistical orbit uncertainty quantities. There is a 99.7% chance the actual value is within given bounds. These statistical calculations assume observational data errors are random. If there are systematic biases (such as timing, reduction or star-catalog errors), results can be optimistic. Because the epoch covariance is mapped using linearized variational partial derivatives, results can also be optimistic for times far from the solution epoch, particularly for objects having close planetary encounters.

NOTE: "n.a." is output if a requested quantity is not available for selected object. For example, azimuth and elevation for a geocentric ephemeris, or uncertainties for an object with no covariance in the database.

SPECIFIC QUANTITIES

1. Astrometric RA & DEC:
   Corrected for light-time only. With respect to the Earth mean equator and equniox of the reference Epoch. If FK4/B1950.0 frame output is selected, elliptic aberration terms are added.

```
Labels:  R.A._(ICRF/J2000.0)_DEC  (HMS/DMS format)
         R.A._( FK4/B1950.0)_DEC  (HMS/DMS format)
         R.A._(J2000.0)_DEC.      (degree format)
         R.A._(B1950.0)_DEC.      (degree format)
```

2. Apparent RA & DEC:
   Apparent right ascension and declination of the target with respect to the center/site body's true-equator and Earth equinox of-date. For non-Earth sites with rotational models, the origin of RA is the meridian containing the Earth equinox of J2000.0. For non-Earth sites without rotational models, RA and DEC are with respect to the REFERENCE FRAME (FK4/B1950 or ICRF/J2000.0) coordinate system. Corrected for light-time, the gravitational deflection of light, stellar aberration, precession and nutation. There is an optional (approximate) correction for atmospheric refraction (Earth only).

```
Labels:  R.A._(a-apparent)__DEC.  (airless, HMS/DMS format)
         R.A._(r-apparent)__DEC.  (refracted, HMS/DMS format)
         R.A._(a-appar)_DEC.      (airless, degrees format)
         R.A._(r-appar)_DEC.      (refracted, degrees format)
```

3. Rates; RA & DEC
   The rate of change of apparent RA and DEC (airless). d(RA)/dt is multiplied by the cosine of declination. Units are ARCSECONDS PER HOUR.

   Labels: dRA*cosD d(DEC)/dt

4. Apparent AZ & EL:
   Apparent azimuth and elevation of target. Corrected for light-time, the gravitational deflection of light, stellar aberration, precession

and nutation. There is an optional (approximate) correction for atmospheric refraction (Earth only). Azimuth measured North(0) -> East(90) -> South(180) -> West(270). Elevation is with respect to plane perpendicular to local zenith direction. TOPOCENTRIC ONLY. Units: DEGREES

```
Labels:  Azi_(a-appr)_Elev  (airless)
         Azi_(r-appr)_Elev  (refracted)
```

5. Rates; AZ & EL

The rate of change of target apparent azimuth and elevation (airless). d(AZ)/dt is multiplied by the cosine of the elevation angle. TOPOCENTRIC ONLY. Units are ARCSECONDS PER MINUTE.

```
Labels:  dAZ*cosE d(ELV)/dt
```

6. X & Y satellite offset & position angle

Satellite differential coordinates WRT the central body along with the satellite position angle. Differential coordinates are defined in RA as X=[(RA_sat – RA_primary)*COS(DEC_primary)], and in DEC as Y=(DEC_sat-DEC_primary). Non-Lunar satellites only. "SatPANG" is CCW angle from the North Celestial Pole to a line from planet center to satellite center. Units: ARCSECONDS (X & Y) and DEGREES (position angle)

```
Labels:  X_(sat-primary)_Y SatPANG
```

7. Local Apparent Sidereal Time

The angle measured westward in the body true-equator of-date plane from the meridian containing the body-fixed observer to the meridian containing the true Earth equinox (defined by intersection of the true Earth equator of date with the ecliptic of date). For non-Earth sites, a somewhat different definition is used. The value returned is measured from the observer meridian to the meridian containing the Earth equinox of the J2000.0 system. TOPOCENTRIC ONLY. Units are HH MM SS.ffff or decimal hours (HH.fffffffff)

```
Labels:  L_Ap_Sid_Time
```

8. Airmass

Relative optical airmass; a measure of extinction. The ratio between the absolute optical airmass at target refracted elevation to the absolute optical airmass at zenith. Based on work of Kasten and Young (Applied Optics, vol. 28 no. 22, 15-Nov-1989). TOPOCENTRIC, ABOVE HORIZON ONLY. Unitless.

```
Labels:  a-mass
```

9. Vis mag. & Surf Bright

Approximate (apparent) visual magnitude & surface brightness. Value for Pluto includes Charon. The Sun's altitude above the Saturn ring-plane is not considered for Saturn. When the Moon is at phase angles < 7 deg. (within 1 day of full), the computed magnitude tends to be ~ 0.12 too small. Surface brightness is returned for asteroids only if a radius is known. It is the average visual magnitude of a square-arcsecond of the illuminated portion of the apparent disk. For observing sites not on the Earth or Moon, planet and satellite values are not available. Sun, comet and asteroid values are. Units are (none) and VISUAL MAGNITUDES PER SQUARE ARCSECOND.

```
Magnitude laws:
  Sun
    APmag= M - 5 + 5*log10(d), where M=4.83, d=distance from Sun (parsecs)
  Asteroids
    APmag= H + 5*log10(delta) + 5*log10(r) -2.5*log10((1-G)*phi1 + G*phi2)
  Comets
    T-mag=M1 + 5*log10(delta) + k1*log10(r)
    N-mag=M2 + 5*log10(delta) + k2*log10(r) + phcof*beta

Surface brightness:
    S-brt= V + 2.5*log10(k*PI*a*b')

   Labels:  APmag S-brt  (Non-comet with known dimensions)
            APmag        (Non-comet with unknown dimensions)
            T-mag N-mag  (comets; total & nuclear magnitudes)
```

10. Illuminated fraction

Percent of target object circular disk illuminated by Sun (phase), as seen by observer. Units are PERCENT.

```
Labels:  Illu%
```

11. Defect of illumination

Angular width of target circular disk diameter not illuminated by Sun. Available only if target radius is known. Units are ARCSECONDS.

```
Labels:  Def_illu
```

12. Angular separation/visibility

The angle between the center of a non-lunar target body and the center of the primary body it revolves around, as seen by the observer. Units are ARCSECONDS.

```
Non-lunar natural satellite visibility codes (limb-to-limb):

/t = Transitting primary body disk, /O = Occulted by primary body disk,
/p = Partial umbral eclipse,        /P = Occulted partial umbral eclipse,
/u = Total umbral eclipse,          /U = Occulted total umbral eclipse,
```

```
      /- = Target is the primary body,    /* = None of above ("free and clear")
```

... the radius of major bodies is taken to be the equatorial value (max) defined by the IAU2000 system. Atmospheric effects and oblateness aspect are not currently considered in these computations. Light-time is.

```
        Labels:   ang-sep/v
```

13. Target angular diameter
The angle subtended by the disk of the target seen by the observer, if it was fully illuminated. The target diameter is taken to be the IAU2000 equatorial diameter. Oblateness aspect is not currently included. Units are ARCSECONDS.

```
        Labels: Ang-diam
```

14. Obs sub-long & sub-lat
The planetographic (geodetic) longitude and latitude of the center of the target disk seen by the observer. Uses the IAU2000 rotation models. For the gas giants only (Jupiter, Saturn, Uranus and Neptune), these longitudes are based on the Set III prime meridian angle, referred to the planet's rotating magnetic field. Latitude is always referred to the body dynamical equator. Note there can be an offset between the dynamical pole and the magnetic pole. Units are DEGREES.

```
        Labels: Ob-lon Ob-lat
```

15. Solar sub-long & sub-lat
The planetographic (geodetic) longitude and latitude of the center of the target disk seen by an observer at the center of the Sun. Uses the IAU2000 rotation models. For the gas giants only (Jupiter, Saturn, Uranus and Neptune), these longitudes are based on the Set III prime meridian angle, referred to the planet's rotating magnetic field. Latitude is always referred to the body dynamical equator. Note there can be an offset between the dynamical pole and the magnetic pole. Units are DEGREES.

```
        Labels: Sl-lon Sl-lat
```

16. Sub Solar Pos. Ang & Dis
Target sub-solar point position angle (CCW with respect to direction of true-of-date Celestial North Pole) and angular distance from the sub-observer point (center of disk) at print time. Negative distance indicates the sub-solar point is on the hemisphere hidden from the observer. Units: DEGREES and ARCSECONDS

```
        Labels: SN.ang SN.ds
```

17. N. Pole Pos. Ang & Dis
Target's North Pole position angle (CCW with respect to direction of true-of-date Celestial North Pole) and angular distance from the sub-observer point (center of disk) at print time. Negative distance indicates N.P. on hidden hemisphere. Units: DEGREES and ARCSECONDS

```
        Labels: NP.ang NP.ds
```

18. Helio eclip. lon & lat
Geometric heliocentric (J2000 or B1950) ecliptic longitude and latitude of target at the instant light leaves it to be observed at print time (print time - 1-way light-time). Units: DEGREES

```
        Labels: hEcl-Lon hEcl-Lat
```

19. Helio range & range-rate
Target apparent heliocentric range ("r") and range-rate ("rdot") as seen by the observer. Units are AU and KM/S.

```
        Labels:    r       rdot
```

20. Observer range & range rate
Target apparent range ("delta") & range-rate ("delta-dot") relative to observer. Units are AU and KM/S.

```
        Labels:   delta  deldot
```

21. One-Way Light-time
Target 1-way light-time, as seen by observer. The elapsed time since light (observed at print-time) left or reflected off the target. Units are MINUTES.

```
        Labels:  1-way_LT
```

22. Speed wrt Sun & obsrvr
Magnitude of velocity of target with respect to the Sun center and the observer at the time light left the target to be observed. Units are KM/S.

```
        Labels:  VmagSn VmagOb
```

23. Sun-Observer-Target angle
Target's apparent solar elongation seen from observer location at print-time. If negative, the target center is behind the Sun. Units are DEGREES.

For observing centers with defined rotation models, an additional marker is output under the column labelled '/r' (for relative position). If there is no rotation model associated with the observing center, no /r column will be present. Under this column,

```
            /T indicates target trails Sun (evening sky)
            /L indicates target leads Sun  (morning sky)
```

NOTE: The S-O-T solar elongation angle is the total separation in any direction. It does not indicate the angle of Sun leading or trailing.

```
        Labels: S-O-T /r
```

24. Sun-Target-Observer angle
Target's apparent PHASE ANGLE as seen from observer location at print time. Units are DEGREES.

```
        Labels: S-T-O
```

25. Target-Observer-Moon (or Interfering_Body) / Illum%
Apparent elongation angle, seen by the observer, between the target body center and the center of a potential visually interfering body (such as the Moon but, more generally, the largest body in the system except for the one the observer is on). Also output is the fraction of the lunar (or IB) disk that is illuminated by the Sun. A negative elongation angle indicates the target center is behind the interfering body. The specific interfering body for an observing site is given in the output header. Units are DEGREES and PERCENT.

```
        Labels: T-O-M/Illu%   (Earth observer, 'M' denoting "Moon")
                T-O-I/Illu%   (Non-Earth observer)
```

26. Observer-Primary-Target angle
Apparent angle between a target satellite, its primary's center and an observer at print time. Units: DEGREES

```
        Labels: O-P-T
```

27. Pos. Ang; radius & -vel
The position angles of the extended Sun->target radius vector ("PsAng") and the negative of the target's heliocentric velocity vector ("PsAMV"), as seen in the plane-of-sky of the observer, measured CCW from reference frame North Celestial Pole. Small-bodies only. Units are DEGREES.

```
        Labels: PsAng PsAMV
```

28. Orbit Plane Angle
Angle between observer and target orbital plane, measured from center of target at the moment light seen at observation time leaves the target. Positive values indicate observer is above the object's orbital plane, in the direction of reference frame +z axis. Small-bodies only. Units: DEGREES.

```
        Labels:  PlAng
```

29. Constellation ID
The 3-letter abbreviation for the constellation name of target's astrometric position, as defined by the IAU (1930) boundary delineation.

```
        Labels: Cnst
```

30. CT-UT =
Difference between uniform Coordinate Time scale ("ephemeris time") a Earth-rotation dependent Universal Time. Prior to 1962, the difference is with respect to UT1 (CT-UT1). For 1962 and later, the delta is with respect to UTC (CT-UTC). Values beyond the next July or January 1st may change if a leap-second is introduced at later date. Units:SECONDS

```
        Labels: CT-UT
```

31. Observer Ecliptic Longitude & Latitude
Observer-centered ecliptic-of-date longitude and latitude of the target's apparent position, corrected for light-time, the gravitational deflection of light and stellar aberration. The ecliptic plane is the Earth's orbital plane at print time. Units: DEGREES

```
        Labels: ObsEcLon    ObsEcLat
```

32. Target North Pole RA & DEC
Right Ascension and Declination (IAU2000 rotation model) of target body's North Pole direction at the time light left the body to be observed at print time. Consistent with requested reference frame; ICRF/J2000.0 or FK4/B1950.0 RA and DEC. Units: DEGREES.

```
        Labels: N.Pole-RA  N.Pole-DC
```

33. Galactic Latitude
Observer-centered Galactic System II (post WW II) latitude of the target's apparent position (corrected for light-time, stellar aberration, precession, nutation and the deflection of light due to the Sun and the most massive body in the planet's system). Units: DEGREES

```
        Labels: GlxLat
```

34. Local Apparent Solar Time
Local Apparent SOLAR Time at observing site. TOPOCENTRIC ONLY. Units are HH.fffffffffff (decimal hours) or HH MM SS.ffff

35. Earth to Site Light-time
Instantaneous light-time of the station with respect to Earth center at print-time. The geometric (or "true") separation of site and Earth center, divided by the speed of light. Units: MINUTES

```
        Labels: 399_ins_LT
```

36. Plane-of-sky RA and DEC pointing uncertainty
Uncertainty in Right-Ascension and Declination. Output values are the formal +/- 3 standard-deviations (sigmas) around nominal position. Units: ARCSECONDS

```
        Labels: RA_3sigma DEC_3sigma
```

37. Plane-of-sky error ellipse
Plane-of-sky (POS) error ellipse data. These quantities summarize the target's 3-dimensional 3-standard-deviation formal uncertainty volume projected into a reference plane perpendicular to the observer's line-of-sight.

```
        Labels:

         SMAA_3sig = Angular width of the 3-sigma error ellipse semi-major
                     axis in POS. Units: ARCSECONDS.

         SMIA_3sig = Angular width of the 3-sigma error ellipse semi-minor
                     axis in POS. Units: ARCSECONDS.

         Theta     = Orientation angle of the error ellipse in POS; the
                     clockwise angle from the direction of increasing RA to
                     the semi-major axis of the error ellipse, in the
                     direction of increasing DEC.  Units: DEGREES.

         Area_3sig = Area of sky enclosed by the 3-sigma error ellipse.
                     Units: ARCSECONDS ^ 2.
```

38. Plane-of-sky ellipse RSS pointing uncertainty
The Root-Sum-of-Squares (RSS) of the 3-standard deviation plane-of-sky error ellipse major and minor axes. This single pointing uncertainty number gives an angular distance (a circular radius) from the target's nominal position in the sky that encompasses the error-ellipse. Units: ARCSECONDS.

```
       Labels: POS_3sigma
```

39. Uncertainties in plane-of-sky radial direction
Range and range rate (radial velocity) formal 3-standard-deviation uncertainties. Units: KM, KM/S

```
       Labels: RNG_3sigma RNGRT_3sig
```

40. Radar uncertainties (plane-of-sky radial direction)
Doppler radar uncertainties at S-band (2380 MHz) and X-band (8560 MHz) frequencies, along with the round-trip (total) delay to first-order. Units: HERTZ and SECONDS

```
       Labels: DOP_S-sig  DOP_X-sig  RT_delay-sig
```

CLOSE-APPROACH TABLES

For asteroids and comets, a close-approach table may be requested. Output is produced only when the selected object reaches a minimum distance within a set spherical radius from a planet, Ceres, Pallas, or Vesta.

User-specifications for this table can include the time-span to check, the radius of detection for planets and asteroids, the maximum uncertainty in time-of-close-approach before the table is automatically cut-off, and whether to output optional error ellipse information projected into the B-plane

The B-plane mentioned above is defined by the three orthogonal unit vectors T, R, and S (the origin being the body center). T lies in the B-plane, pointing in the direction of decreasing celestial longitude. R lies in the B-plane, pointing in the direction of decreasing celestial latitude (south). S is directed along the relative velocity vector at body encounter, perpendicular to the B-plane, and thus R and T. The B vector is the vector in the plane from the body to the point where the incoming object's velocity asymptote pierces the R-T plane. Note the B-plane is defined only when the incoming object is hyperbolic with respect to the body.

For objects with covariances, statistical quantities are output for each close-approach. All tabulated statistical quantities (MinDist, MaxDist, TCA3Sg, Nsigs and P_i/p) are based on a linearized covariance mapping in which higher-order (small) terms in the variational partial derivatives of the equations of motion are dropped.

Due to possible non-linearities in any given object's actual dynamics, this can result in significant errors at epochs distant in time from the solution epoch. Consequently, long linearized mappings (thousands, or hundreds, or sometimes just dozens of years from the present time) should be considered approximate, pending additional analysis, especially in these cases:

A) objects with numerous close planetary encounters (dozens),
B) objects with very close planetary encounters (< 0.01 AU),
C) objects with very short data arcs (days or weeks).

While linearized projections will tend to indicate such cases with obviously rapid uncertainty growth, the specific numbers output can tend to understate orbit uncertainty knowledge.

Possible output quantities are described below. "Nominal" effectively means "highest-probability for the given orbit solution", although there can be other possible orbits of equal probability. If there is no covariance, no statistical quantities are returned.

Date (CT) =
Nominal close-approach date (Coordinate Time). Calendar dates prior to 1582-Oct-15 are in the Julian calendar system. Later calendar dates are in the Gregorian system.

Body =
Name or abbreviation of the planetary body or major asteroid being closely approached by the selected small-body.

CA Dist =
Nominal close-approach distance at the close-approach time. Units: AU

MinDist =
Minimum close-approach distance possible (formal 3 standard-deviations with linearized covariance mapping). Units: AU

MaxDist =
Maximum close-approach distance possible (formal 3 standard-deviations with linearized covariance mapping). Units: AU

Vrel =
Relative velocity of the object and the body it is approaching at the nominal time of close-approach. Units: KM/S

TCA3Sg =
Close-approach-time 3-standard deviation uncertainty. Units: MINUTES

SMaA =
3-sigma error ellipse semi-major axis projected into the B-plane at nominal time of closest-approach. Units: KM

SMiA =
3-sigma error ellipse semi-minor axis projected into the B-plane at nominal time of closest-approach. Units: KM

Gamma =
Orientation angle of error ellipse in the B-plane. Counter-clockwise angle from the B vector to the semi-major axis of the error ellipse. Units: DEGREES

Nsigs =
The number of standard deviations (sigmas) required for the error ellipse to intersect the body being closely approached. Units: STANDARD DEVIATIONS

P_i/p =
Linearized probability of the object impacting the body.

UNDERSTANDING RISE, TRANSIT AND SET INDICATORS

There are 2 ways the system can be used to mark rise, transit and set (RTS) conditions: activate the RTS-only print option OR produce a general observer table with step-size less than 30 minutes.

NORMAL_TABLE RTS-MARKER MODE

RTS is indicated automatically during normal observer table generation, when the step-size is less than 30 minutes. Markers are placed to indicate the event occurred at some point in the previous step. Thus, precision of the indicator depends on the step-size selected. For this mode, rise and set are always with respect to the true-visual-horizon reference plane (TVH), described below.

RTS-ONLY PRINT MODE

The advantage of this mode is it allows production of a more compact RTS table over a longer time-span than does the "normal" table generation mode.

When RTS-only print is selected, the program will search for the events at a user-specified resolution, from 1 to 9 minutes. Output will be generated ONLY for these three events. The marker symbols in the table indicate that the event took place sometime in the previous

step interval.

This RTS-only mode can be turned on at two different points in the program:

1. Preferably, when specifying the ephemeris/search step-size
2. ... but also in the "change defaults" prompt structure

Three types of criteria are available for the rise and set conditions, relative to an input elevation angle (nominally 0 degrees). Select by specifying, when prompted at #1 or #2, one of these symbols:

TVH
True visual horizon plane. The horizon seen by an observer on the reference ellipsoid. Allows for horizon dip effect and refraction, but not local topography.
GEO
Geometric horizon plane. The horizon is defined by the plane perpendicular to the reference ellipsoid local zenith (no horizon dip). Refraction is allowed for.
RAD
Radar case. Geometric horizon plane, no refraction.

For example, when prompted for the step-size, one could enter "5 min GEO' to search, at five-minute steps, for the refracted rise/set relative to the geometric horizon.

BACKGROUND DESCRIPTION

Rise and set elevations are taken to be the maximum of 0 or the input elevation cut-off value [0-90 deg], set in the "change defaults" prompt section. Thus, if there are local hills, one could set the cut-off at 10 degrees and get RTS relative to that elevation.

At low elevations, these rise/set times should be viewed as approximations, realistically good to perhaps only 1-2 minutes at the horizon due to local atmospheric variation and topography.

To speed RTS-only searches, use the largest step-size compatible with the required accuracy. For example, considering the inherent atmospheric instability at the horizon, one should rarely need to identify rise/set to better than 5 minute accuracy. Setting a search-step of 5 minutes will then produce a table 5 times faster than 1 minute searching.

The program computes approximate refraction angles assuming yellow-light observations at 10 deg C sea-level with pressure of 1010 millibars. Corrected coordinates should be accurate to < 10 arcsec, but errors may be much larger near the horizon (+- 0.3 deg) or fluctuate unpredictably with local weather.

Both Moon and Sun rise/set are based on when the refracted upper limb of the object reaches the specified elevation. Transit is based on the center of the target body.

CONSTELLATION IDENTIFICATION

One output value that may be requested for an observer table is the constellation it is observed to be in (corrected for light-time). The output field will contain a three letter abbreviation of the constellation name, from the list shown below.

Constellation boundaries are those delineated by Gould (1877) and Delporte (1930) under the auspices of the International Astronomical Union.

Abbrev.	Constellation Name		Abbrev.	Constellation Name
And	Andromeda		Leo	Leo
Ant	Antila		LMi	Leo Minor
Aps	Apus		Lep	Lepus
Aqr	Aquarius		Lib	Libra
Aql	Aquila		Lup	Lupus
Ara	Ara		Lyn	Lynx
Ari	Aries		Lyr	Lyra
Aur	Auriga		Men	Mensa
Boo	Bootes		Mic	Microscopium
Cae	Caelum		Mon	Monoceros
Cam	Camelopardis		Mus	Musca
Cnc	Cancer		Nor	Norma
CVn	Canes Venatici		Oct	Octans
CMa	Canis Major		Oph	Ophiuchus
CMi	Canis Minor		Ori	Orion
Cap	Capricornus		Pav	Pavo
Car	Carina		Peg	Pegasus

Cas	Cassiopeia		Per	Perseus	
Cen	Centaurus		Phe	Phoenix	
Cep	Cepheus		Pic	Pictor	
Cet	Cetus		Psc	Pisces	
Cha	Chamaeleon		PsA	Pisces Austrinus	
Cir	Circinus		Pup	Puppis	
Col	Columba		Pyx	Pyxis	
Com	Coma Berenices		Ret	Reticulum	
CrA	Corona Australis		Sge	Sagitta	
CrB	Corona Borealis		Sgr	Sagittarius	
Crv	Corvus		Sco	Scorpius	
Crt	Crater		Scl	Sculptor	
Cru	Crux		Sct	Scutum	
Cyg	Cygnus		Ser	Serpens	
Del	Delphinus		Sex	Sextans	
Dor	Dorado		Tau	Taurus	
Dra	Draco		Tel	Telescopium	
Equ	Equuleus		Tri	Triangulum	
Eri	Eridanus		TrA	Triangulum Australe	
For	Fornax		Tuc	Tucana	
Gem	Gemini		UMa	Ursa Major	
Gru	Grus		UMi	Ursa Minor	
Her	Hercules		Vel	Vela	
Hor	Horologium		Vir	Virgo	
Hya	Hydra		Vol	Volans	
Hyi	Hydrus		Vul	Vulpecula	
Ind	Indus				
Lac	Lacerta				

SPK File Generation

Introduction:

An SPK file is a binary file which may be smoothly interpolated to retrieve an object's position and velocity at any instant within the file time-span. Such files may be used as input to visualization and mission design programs, allowing them to quickly retrieve accurate target body observation and data analysis ephemerides without having to repeatedly integrate equations of motion. An SPK file could be considered a "recording" of the integrator.

SPK stands for "Spacecraft and Planet Kernel". It is a file element of the SPICE system devised and maintained by the NAIF (Navigational and Ancillary Information Facility) team at JPL. SPK files may hold ephemerides for any kind of spacecraft, vehicle or solar system body, but the SPK files produced by Horizons are only for comets and asteroids.

Potential users are advised that programming and science/math skills at an advanced college level are needed to utilize these files. Users must have a computer with 25-50 Mbytes of disk space, 8 Mbytes of available RAM and a FORTRAN or C compiler. The user's own code must be capable of calling FORTRAN or C modules. Internet FTP capability is needed to obtain the necessary SPICE components as well as the SPK files generated by Horizons.

For information on SPK files in general, contact

Charles.H.Acton-Jr@jpl.nasa.gov (NAIF Team Leader)

or see web site http://pds-naif.jpl.nasa.gov/.

Horizons Implementation:

IMPORTANT:

These informal file releases should not be used for "category A" flight project purposes (involving the safety and success of spacecraft hardware and mission) without first contacting ...

Donald.K.Yeomans@jpl.nasa.gov
Supervisor, Solar System Dynamics Group, 818-354-2127

A particular object's orbit may be insufficiently well-determined, over the chosen time-span, to be suitable for some high-precision purposes.

Background:

SPK files can be produced only with the telnet interface. Horizons allows a maximum of 20 small-bodies per SPK file. To construct an SPK for a comet or asteroid, Horizons integrates the object's trajectory over a user-specified time span greater than 32 days, but less than 200 years. The position components, at discrete steps, over some interval, are fit to a series of Chebyshev polynomials. When a users' application program reads the SPK file, the appropriate polynomials are accessed and interpolated to retrieve the requested state.

SPK files are capable of storing trajectory data with a fidelity greater than 1 millimeter (more accurately than should ever be required). In practice, it is the Chebyshev fit that determines how closely the SPK interpolation matches the integrator. The typical trade-off is that higher fidelity SPK files are obtained by fitting higher degree polynomials to smaller time intervals. The cost for increased accuracy is larger file size.

File Fidelity:

Choosing the best way to represent a trajectory in a file is complicated by the wide range of small-body orbits and anomalies such as close-approaches to major planets. Horizons seeks to strike a rough balance between file size and file fidelity, valuing fidelity more than file size.

Prior to the integration, a default mesh (state vector interval) is selected for the polynomial fits. There is the "loose" mesh for main-belt objects (eccentricity less than 0.35, semi-major axis greater than 2.3 AU). This covers the majority of objects. Integrator states are preserved to the meter level or less (1-sigma) for most objects.

There is a "standard mesh" that will fit all but a few objects well; close-approaches are described accurately to the 10-50 meter range and < 1 meter at other times. File sizes are 4 times larger than "loose" mesh objects.

Finally, for a few objects, a "tight" mesh will be necessary. File sizes are 4x larger than "standard", 16x larger than "loose".

Mesh assignment is automatic, but not all cases requiring a tight mesh can be detected in advance (which is why this is being discussed). At the end of an integration, a summary of polynomial fit maximum errors is displayed:

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
A-posteriori SPK fidelity estimate (rel. to integrator):
     Max. error (3 std. dev)           Time
     ------------------------ ----------------------
  X: 0.7104212997280315D-03 m 1998-May-09 12:00:00.000
  Y: 0.1287005692494599D-02 m 1998-May-09 12:00:00.000
  Z: 0.7502616895491441D-03 m 1998-May-09 12:00:00.000
RSS: 0.1650446811753079D-02 m 1998-May-09 12:00:00.000
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

This shows the maximum three standard deviation error detected in the Chebyshev fit to the integrator position vector components. The maximum root-sum-square (RSS) of component error is also shown. If the error from the default mesh selection is too large for your application, contact

Jon.D.Giorgini@jpl.nasa.gov

for instructions on forcing Horizons to a tighter mesh and improving fidelity.

The above data, along with other summary information, is stored in the SPK file comment area. It can be read using the "spacit" or "commnt" utility in the SPICE Toolkit distribution.

Transferring SPK files:

Within the Horizons system, SPK files are created as binary files on a Sun UltraSparc/UNIX platform. These files can be used on several popular platforms, but may be unreadable on others. Reasons for this include:

1. Data-type representation (machine word-size)
2. Floating point representations (IEEE or not)
3. Byte order (least significant byte first vs. last)

If you are using a verion of the SPICE Toolkit higher than 52, you will be able to directly read Horizons binary files on any platform. If not, the machine you intend to use the SPK file on thus falls into one of two possible categories:

Compatible systems:

If your system has 32-bit words, IEEE floating-point, and is "big-endian" (stores highest order byte first) like the Sun UltraSparc, you will be able to use Horizons-generated binary SPK files directly; respond "no" to the "transfer format" prompt and use the binary mode of FTP to retrieve the file. Known compatible machines are the HP 9000 series, Motorola 68K series (MacIntosh), Silicon Graphics and NeXT, among others.

Incompatible systems:

Known incompatible machines would be the Intel series (80486, Pentium, etc.), DEC Alpha and VAX which have reversed byte-orders and/or non-IEEE floating-point. To obtain an SPK for one of these platforms, respond "yes" to the "transfer format" prompt. The binary file will be converted to a transfer file. Once you FTP this file to your system, using FTP ASCII mode, you MUST run the program 'spacit' or 'tobin' (included in your SPICE Toolkit) to produce a binary-compatible SPK for your machine.

STATEMENT OF EPHEMERIS LIMITATIONS

To produce an ephemeris, observational data (optical, VLBI, radar & spacecraft) containing measurement errors are combined with dynamical models containing modeling imprecisions. A best fit is developed to statistically minimize those errors. The resulting ephemeris has an associated uncertainty that fluctuates with time.

For example, only a limited percentage of asteroid orbits are known to better than 1 arcsec in the plane-of-sky over significant periods of time. While 1991 JX center-of-mass was known to within 30 meters along the line-of-sight during the 1995 Goldstone radar experiment, errors increase outside that time-span. Uncertainties in major planet ephemerides range from 10cm to 100+ km in the state-of-the-art JPL/DE-405 ephemeris, used as the basis for spacecraft navigation, mission planning and radar astronomy.

Cartesian state vectors are output in all their 16 decimal-place glory. This does not mean all digits are physically meaningful. The full-precision may be of interest to those studying the ephemerides or as a source of initial conditions for subsequent integrations.

On top of this basic uncertainty, for osculating element output, GM is rarely known to better than 5 significant figures.

For observer angular output tables, purely local atmospheric conditions will affect "refraction-corrected" apparent places by several arcseconds, more at the horizon.

Small-body elements are reported in the optical frame (i.e. FK5/J2000.0). This frame is currently thought to differ by no more than 0.01 arcseconds from the radio frame ICRF93/J2000.0 of the planetary ephemeris DE-405. Until a generally agreed upon transformation from one frame to the other is defined and implemented, they will be treated by this program as being the same.

The Earth is assumed to be a rigid body and solid Earth tides affecting station location are not included. Of course, precession and nutation effects are included, as is polar motion. CT-TAI terms less than 20 usec are omitted. These and other Earth-model approximations result in topocentric station location errors, with respect to the reference ellipsoid, of less than 20 meters. However, many optical site positions (latitude and longitude) are known far less accurately and can be many kilometers off.

Relativistic effects are included in all planet, lunar and small body dynamics, excluding satellites. Relativity is included in observables via 2nd order terms in stellar aberration and the deflection of light due to gravity fields of the Sun (and Earth, for topocentric observers).

Deflections due to other gravity fields can potentially have an effect at the 10^-4 arcsec level but are not currently included here. Satellites of other planets, such as Jupiter could experience deflections at the 10^-3 arcsec level as well. Light time iterations are Newtonian. This affects light-time convergence at the millisecond level, position at ~10^-6 arcsec level.

For many small natural satellites, the orbit orientation is well known, but the position of the body along the ellipse is not. Errors may be significant, especially for the lesser satellites of outer planets. Satellite osculating elements output by Horizons should NOT be used to initialize a separate integration or extrapolation. Such elements assume Keplerian motion (two point masses, etc.) which does not match, for example, kinematic models such as a precessing ellipse, used for some satellites. One would do better extrapolating mean orbital elements at http://ssd.jpl.nasa.gov/sat_elem.html.

IF YOUR CAREER OR SPACECRAFT DEPENDS ON A NON-LUNAR NATURAL SATELLITE OR SMALL-BODY EPHEMERIS, CONTACT JPL BEFORE USING IT. YOU *MUST* HAVE ADDITIONAL INFORMATION TO CORRECTLY UNDERSTAND EPHEMERIS LIMITATIONS AND UNCERTAINTIES.

LONG-TERM EPHEMERIS

SOLAR SYSTEM MODEL:

The JPL DE-406/LE-406 extended ephemeris covers the interval from 3000 B.C. to A.D. 3000. This ephemeris is identical to the shorter DE-405 in the sense it is the same data-fit (solution) and the same numerical integration as DE-405. However, it has been stored with slightly less accuracy to reduce its size.

For the Moon, DE-406 recovers the original integrator state to within 1 meter, other bodies within 25 meters (maximum error). This difference can be less than the uncertainty associated with the trajectory solution itself, thus is insignificant for all but the most

specialized circumstances. The short-span version, DE-405, recovers the integrator state to the millimeter level.

Horizons uses the long-term DE-406/LE-406 for the following objects:

Objects	ID code #
All planet barycenters	0,1,2,3,4,5,6,7,8,9
Sun	10
Moon	301
Mercury	199
Venus	299
Earth	399
Mars	499

Satellites and outer solar-system planet-centers each have various shorter intervals, as warranted by their observational data arc. Comets and asteroids are available only over the A.D. 1599 to A.D. 2200 interval of the DE-405 ephemeris they are integrated against. (Only a few dozen small-bodies have sufficiently well-known orbits to justify rigorous integration over time-spans of hundreds of years.)

PRECESSION MODEL:

For the time-span of 1799-Jan-1 to 2202-Jan-1, the official IAU precession model [16] of Lieske is used. As published, this model is valid for only ~200 years on either side of the J2000.0 epoch. This is due to round-off error in the published coefficients and truncation to a 3rd order polynomial in the expressions for the Euler rotation angles. Therefore, outside this interval, the long-term precession and obliquity model [17] of Owen is used to maintain accuracy in the calculation of apparent ("of-date") quantities.

This model is a rigorous numerical integration of the equations of motion of the celestial pole using Kinoshita's model for the speed of luni-solar precession.

NUTATION MODEL:

The IAU (1980) model [18] of Wahr is used. This is the same table printed in the 1992 Explanatory Supplement to the Astronomical Almanac. Note there is an error in the Explanatory Supplement for the Node term, given on p. 114 as:

OMEGA = 135deg 2'40.280" + ...

This system uses the correct formulation:

OMEGA = 125deg 2'40.280" + ...

UNIVERSAL TIME (CT -> UT Conversion):

This program internally uses the CT time-scale of the ephemerides (the independent variable in the equations of motion). To produce the more familiar Universal Time (UT) output tied to the Earth's rotation, it is necessary to use historical reconstructions of old or ancient observations of constrained events, such as eclipses, to derive a CT-UT difference. This program currently uses the analyses of [12-15] as follows:

Span	CT-UT offset ("delta-t")	Type	Argument (T=...)
3000 BC to AD 948	31*T*T	UT1	cent. since 1820
AD 948 to AD 1620	50.6D0+67.5D0*T+22.5D0*T*T	UT1	cent. since J200.0
AD 1620 to AD 1962	Smoothed table	UT1	
AD 1962 to Present	EOP file data	UTC	

For the modern UTC era specifically, the calculation is as follows:

```
CT - UTC = (CT - TAI) + (TAI - UTC)
```

... where

```
CT  - TAI = 32.184 + 1.657E-3 * SIN( M + 0.01671*SIN(M) )
        M = 6.239996 +  T * 1.99096871E-7
        T = CT or TAI seconds past J2000.0 epoch

TAI - UTC = interpolated from current EOP file.
```

... dropping terms less than about 20 usec in CT-TAI.

As one progresses to earlier times, particularly those prior to the 1620 telescopic data span, uncertainties in UT determination generally (though not always and not uniformly) increase due to less precise observations and sparser records. At A.D. 948, uncertainty (not necessarily error) can be a few minutes. At 3000 B.C., the uncertainty in UT is about 4 hours. The TT time scale, being uniform, does not

have this uncertainty, but is not directly related to Earth's rotation (local time) either.

GREENWICH MEAN SIDEREAL TIME:

GMST, used for topocentric ephemerides, is related to UT1 using an expression consistent with the IAU 1976 system of constants, as shown on p. 50 of the Explanatory Supplement (1992), along with the new more accurate 1997 IAU equinox equation.

HIGH PRECISION EARTH ORIENTATION PARAMETER (EOP) MODEL

The EOP file is currently updated twice a week based on GPS and other Earth-monitoring measurements. Horizons uses it to obtain calibrations for UT1-UTC, polar motion and nutation correction parameters necessary to determine the rotation from the Earth-fixed reference frame to an inertial reference frame. The EOP file provides data from 1962 to the present, with predictions about 78 days into the future from the date of file release. For times outside the available interval, Horizons uses the last value available in the file as constants. For CT-UT calculations, it switches to the different models described above.

Because EOP values are fit to data, it is possible an ephemeris may differ slightly from one produced days or weeks or months later, especially, if the original ephemeris extended into the predicted region of the EOP file. The most recent ephemeris will be more accurate, but if it is necessary to reproduce results exactly, contact JPL. EOP files are archived and the one used in your initial run (indicated in your output) can be retrieved. Generally, any numeric change will be very small and almost always negligible in a practical sense.

BODY ROTATIONS:

The modern 2000 IAU rotational models for the planets and satellites are simply extended in time as necessary.

BACKGROUND

- Comet and asteroid orbits are INTEGRATED from initial conditions stored in the JPL-maintained DASTCOM database.
- Planet and satellite ephemerides are INTERPOLATED from files previously generated by JPL, such as the DE-405 (or higher) planetary ephemeris.
- SMALL BODY DATA SCREENS are from the JPL DASTCOM database. These display constants ARE ACTUALLY USED to produce the ephemeris.
- MAJOR BODY DATA SCREEN CONSTANTS are from "Astrometric and Geometric Properties of Earth and the Solar System", Charles Yoder (JPL), published in "Global Earth Physics: A Handbook of Physical Constants", AGU Reference Shelf 1.
- MAJOR BODY DATA SCREEN CONSTANTS are presented for your information (FYI) only and ARE NOT USED to generate the ephemeris output (see below). While an effort has been made to insure their accuracy, suitability of these DISPLAY constants for any given purpose must be determined by individual users. Users should be aware there is often more than one determination in the literature for many of these constants and that they are subject to revision as more data are accumulated.

LIST OF MAJOR BODY EPHEMERIDES ON-LINE

The following major body ephemerides are currently on-line. Newly discovered satellites are also available, although they are not shown below. Planet centers are considered the 99th satellite of the system barycenter. Satellites 506-513, 607, 716-721 and 802 do not have defined rotational models in the 2000 IAU report.

```
000 Solar System Barycenter
    10  Sun

001 Mercury barycenter
    199 Mercury

002 Venus barycenter
    299 Venus

003 Earth barycenter
    399 Earth
    301 Moon

004 Mars barycenter
    499 Mars
```

```
    401 Phobos      402 Deimos

005 Jupiter barycenter
    599 Jupiter
    501 Io          502 Europa      503 Ganymede    504 Callisto
    505 Amalthea    506 Himalia     507 Elara       508 Pasiphae
    509 Sinope      510 Lysithea    511 Carme       512 Ananke
    513 Leda        514 Thebe       515 Adrastea    516 Metis

006 Saturn barycenter
    699 Saturn
    601 Mimas       602 Enceladus   603 Tethys      604 Dione
    605 Rhea        606 Titan       607 Hyperion    608 Iapetus
    609 Phoebe      610 Janus       611 Epimetheus  612 Helene
    613 Telesto     614 Calypso     615 Atlas       616 Prometheus
    617 Pandora     618 Pan

007 Uranus barycenter
    799 Uranus
    701 Ariel       702 Umbriel     703 Titania     704 Oberon
    705 Miranda     706 Cordelia    707 Ophelia     708 Bianca
    709 Cressida    710 Desdemona   711 Juliet      712 Portia
    713 Rosalind    714 Belinda     715 Puck        716 Caliban
    717 Sycorax     718 (1986U10)   719 (1999U1)    720 (1999U2)
    721 (1999U3)

008 Neptune barycenter
    899 Neptune
    801 Triton      802 Nereid      803 Naiad       804 Thalassa
    805 Despina     806 Galatea     807 Larissa     808 Proteus

009 Pluto barycenter
    999 Pluto
    901 Charon
```

SOURCES AND REFERENCES FOR PRIMARY EPHEMERIS DATA

Planets

Standish, E.M., XX Newhall, J.G. Williams, and W.M. Folkner. JPL Planetary and Lunar Ephemerides, DE403/LE403. JPL Interoffice Memorandum 314.10-127 dated May 22, 1995.

Natural Satellites

Satellite	Theory	Ephemeris References
Phobos & Deimos	MARSAT (Analytic)	Jacobson et al. (1989)
Galileans	GALSAT(E5, Analytic)	Lieske (1995)
Minor Jovians	Precessing ellipse	Jacobson (1994)
Outer Jovians	Numerical Integration	Jacobson (1991)
Major Saturnians	Numerical Integration	Jacobson (1996a)
Phoebe	Numerical Integration	Jacobson (1996c)
Inner Saturnians	Precessing ellipse	Jacobson (1995)
Saturn co-orbiters	Numerical Integration	Jacobson (1995)
Saturn librators	Numerical Integration	Jacobson (1995)
Major Uranians	GUST (Analytic)	Laskar & Jacobson (1987)
Minor Uranians	Precessing ellipse	Jacobson (1996b)
Triton	Numerical Integration	Jacobson et al. (1991)
Nereid	Numerical Integration	Jacobson et al. (1991)
Inner Neptunians	Precessing ellipse	Owen et al. (1991)
Charon	Dynamic conic	Tholen (1990)

References For Natural Satellite Ephemerides:

1. Jacobson, R.A., 1991. Outer Jovian Satellite Ephemerides for the Galileo Project. JPL Interoffice Memorandum 314.6-1261 (JPL

internal document).

2. Jacobson, R.A., 1994. Revised Ephemerides for the Inner Jovian Satellites. JPL Interoffice Memorandum 314.10-101 (JPL internal document).

3. Jacobson, R.A., 1995. The Orbits of the Minor Saturnian Satellites. Bulletin, American Astronomical Society, vol. 27, No.3, p. 1202-1203.

4. Jacobson, R.A., 1996a. Update of the Major Saturnian Satellite Ephemerides. JPL Interoffice Memorandum 312.1-96-012 (JPL internal document).

5. Jacobson, R.A., 1996b. Updated Ephemerides for the Minor Uranian Satellites. JPL Interoffice Memorandum 312.1-96-014 (JPL internal document).

6. Jacobson, R.A., 1996c. Update of the Ephemeris for Phoebe. JPL Interoffice Memorandum 312.1-96-024 (JPL internal document).

7. Jacobson, R.A., Synnott, S.P., and Campbell, J.K., 1989. The Orbits of the Satellites of Mars from Spacecraft and Earthbased Observations. Astronomy and Astrophysics, 225, 548.

8. Jacobson, R.A., Riedel, J.E. and Taylor, A.H., 1991. The Orbits of Triton and Nereid from Spacecraft and Earthbased Observations. Astronomy and Astrophysics, 247, 565.

9. Laskar, J. and Jacobson, R.A., 1987. GUST86. An Analytic Ephemeris of the Uranian Satellites. Astronomy and Astrophysics, 188, 212.

10. Lieske, J.H., 1995. Galilean Satellite Ephemerides E5. JPL Engineering Memorandum 312-583 (JPL internal document).

11. Owen, W.M., Vaughan, R.M., and Synnott, S.P., 1991. Orbits of the Six New Satellites of Neptune. Astronomical Journal, 101, 1511.

12. Tholen, D. and Buie, M.W., 1990. Further Analysis of Pluto-Charon Mutual Event Observations - 1990. Bulletin, American Astronomical Society, vol. 22, No.3, p. 1129.

Comets and Asteroids

Sources of Orbital Elements for Comets and Asteroids

1. Minor Planet Circulars (MPC) published by the Minor Planet Center, 60 Garden St., Cambridge, Massachusetts 02138 http://cfa-www.harvard.edu/cfa/ps/mpc.html

2. The Lowell Observatory Database of Asteroid Orbits (E.L.G. Bowell) http://www.lowell.edu

3. Solar System Dynamics Group/Jet Propulsion Laboratory (JPL) D.K. Yeomans, Supervisor

Cometary Magnitude Parameters

1. International Comet Quarterly (D.W.E. Green, editor), 60 Garden St., Cambridge, Massachusetts, 02138

2. Charles Morris, Jet Propulsion Laboratory, Pasadena, California 91109

Asteroid Physical Parameters

Radius and Albedo:

1. Tedesco, E.F. (1995) "IMPS Diameters and Albedos V1.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

2. McFadden, L.A. et al. (1989) In Asteroids II, p. 456.

3. Williams, J.G. (1990) Private Communication.

Taxonomic Type ("Spectral Type"):

1. Tholen, D.J. (1989) "Asteroid Taxonomy V1.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

2. Binzel, R.P. and Xu, S. (1993) Science 216:186-191.

Rotation Period:

1. Harris, A.W. (1996) "Asteroid Lightcurve Derived Data V2.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

Magnitude Parameters:

1. Minor Planet Circulars (MPC) published by the Minor Planet Center, 60 Garden St., Cambridge, Massachusetts 02138 http://cfa-www.harvard.edu/cfa/ps/mpc.html

Constants and Model References

Major body (planet/satellite) GM and AU definitions ACTUALLY USED (as opposed to the FYI data screens) are from the DE-405 ephemeris, a significant improvement over the earlier DE-200. Other planet and satellite constants used by this software, such as radii, rotation and orientation, are based on the following sources:

1.
`Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000', Celestial Mechanics and Dynamical Astronomy 82: 83-110, 2002.

2.
`The Astronomical Almanac', 1993.

3.
`Planetary Geodetic Control Using Satellite Imaging', Journal of Geophysical Research, Vol. 84, No. B3, March 10, 1979, by Thomas C. Duxbury.

4.
Letter from Thomas C. Duxbury to Dr. Ephraim Lazeryevich Akim, Keldish Institute of Applied Mathematics, USSR Academy of Sciences, Moscow, USSR.

Most values are from the `IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000'. The exceptions are:

- Radii for the Sun are from the above reference [2].
- The second nutation precession angle (M2) for Mars is represented by a quadratic polynomial in the IAU2000 report. Current software cannot handle this term (which is extremely small), so the polynomial is truncated to a linear one.
- The expressions for the pole and prime meridian of Neptune given in the IAU report include trigonometric terms which current software doesn't yet handle. These terms are omitted.
- For several satellites, the IAU2000 report either gives a single radius value or a polar radius and a single equatorial radius. Current software uses a triaxial ellipsoid model that requires three radii. In the cases listed below, additional values have been supplied in order to allow the software to function.

The affected satellites are:

```
Body      NAIF ID code
----      ------------
Thebe     514
Metis     516
Helene    612
Caliban   716      (no IAU value)
Sycorax   717      (no IAU value)
Larissa   807
Vesta     20000004 (no IAU value)
```

Airmass computation is based on:

5.
Kasten, F., Young, A., "Revised Optical Air Mass Tables and Approximation Formula", Applied Optics, vol 28, no. 22, p. 4735-4738, Nov. 15,

1989.

Refraction computation is based on [6-7]:

6.
Saemundsson, T., *Sky & Telescope*, July, 1986, p.70.

7.
Meeus, J., "Astronomical Algorithms", 1991, p. 101-102.

Constellation identification based on [8-9,(10-11)]:

8.
Roman, N.G. 1987, "Identification of a Constellation from a Position", *Publ. Astronomical Society of the Pacific* **99**, 695-699.

9.
Warren, Wayne H., Jr., (1997, GSFC) private communication.

10.
Delporte, E. 1930, *Delimitation Scientifique des Constellations*, Cambridge, Cambridge University Press.

11.
Gould, B.A., 1877, *Uranometria Argentina, mapas* (Buenos Aires, Argentina: Observatorio Nacional)

Long-term CT-UT offset calculations based on:

12.
priv. comm. Morrison (1980).

13.
Stephenson, F.R., Houlden, M.A., *Atlas of Historical Eclipse Maps*, Cambridge Univ. Press, p X, (1986).

14.
Stephenson, F.R, Morrison, L.V., "Long-term Changes in the Rotation of the Earth: 700 B.C. to A.D. 1980", *Phil. Trans. R. Soc. London* **313**, 47-70 (1984)

15.
Stephenson, F.R., Morrison, L.V., "Long-term Fluctuations in the Earth's Rotation: 700 BC to AD 1990", *Phil. Trans. R. Soc. London* **351**, p. 165-202 (1995)

Precession (IAU) from 1799-Jan-1 to 2202-Jan-1:

16.
Lieske, J., "Precession Matrix Based on IAU (1976) System of Astronomical Constants", *Astron. Astrophys.* **73**, 282-284, 1979.

Precession (long-term) before 1799-Jan-1 and after 2202-Jan-1:

17.
Owen, William M., Jr., (JPL) *A Theory of the Earth's Precession Relative to the Invariable Plane of the Solar System*, Ph.D. Dissertation, University of Florida, 1990.

Nutation:

18.
Table 1,"Proposal to the IAU Working Group on Nutation", John M. Wahr and Martin L. Smith 1979. Adopted 1980.